



# Pilot-Induced Oscillation Research: Status at the End of the Century

*Compiled by Mary F. Shafer and Paul Steinmetz  
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National Aeronautics and  
Space Administration

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**April 2001**

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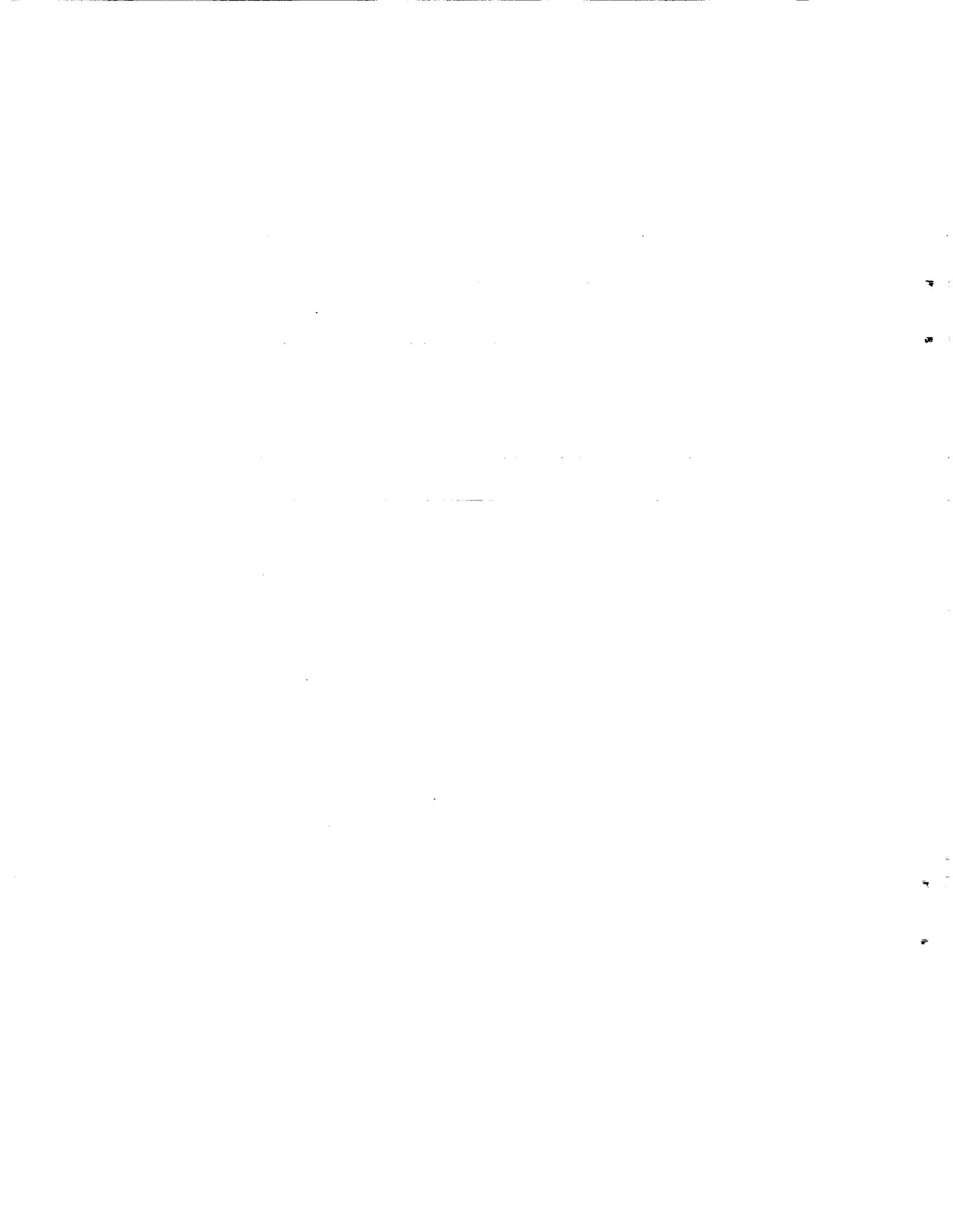
## Foreword

“Pilot-Induced Oscillation Research: The Status at the End of the Century,” a workshop held at NASA Dryden Flight Research Center on 6–8 April 1999, may well be the last large international workshop of the twentieth century on pilot-induced oscillation (PIO). With nearly a hundred attendees from ten countries and thirty presentations (plus two that were not presented but are included in the proceedings) the workshop did indeed represent the status of PIO at the end of the century.

These presentations address the most current information available, addressing regulatory issues, flight test, safety, modeling, prediction, simulation, mitigation or prevention, and areas that require further research. All presentations were approved for publication as unclassified documents with no limits on their distribution.

This proceedings include the viewgraphs (some with authors’ notes) used for the thirty presentations that were actually given as well as two presentations that were not given because of time limitations. Four technical papers on this subject that offer this information in a more complete form are also included. In addition, copies of the related announcements and the program are incorporated, to better place the workshop in the context in which it was presented.

Mary F. Shafer



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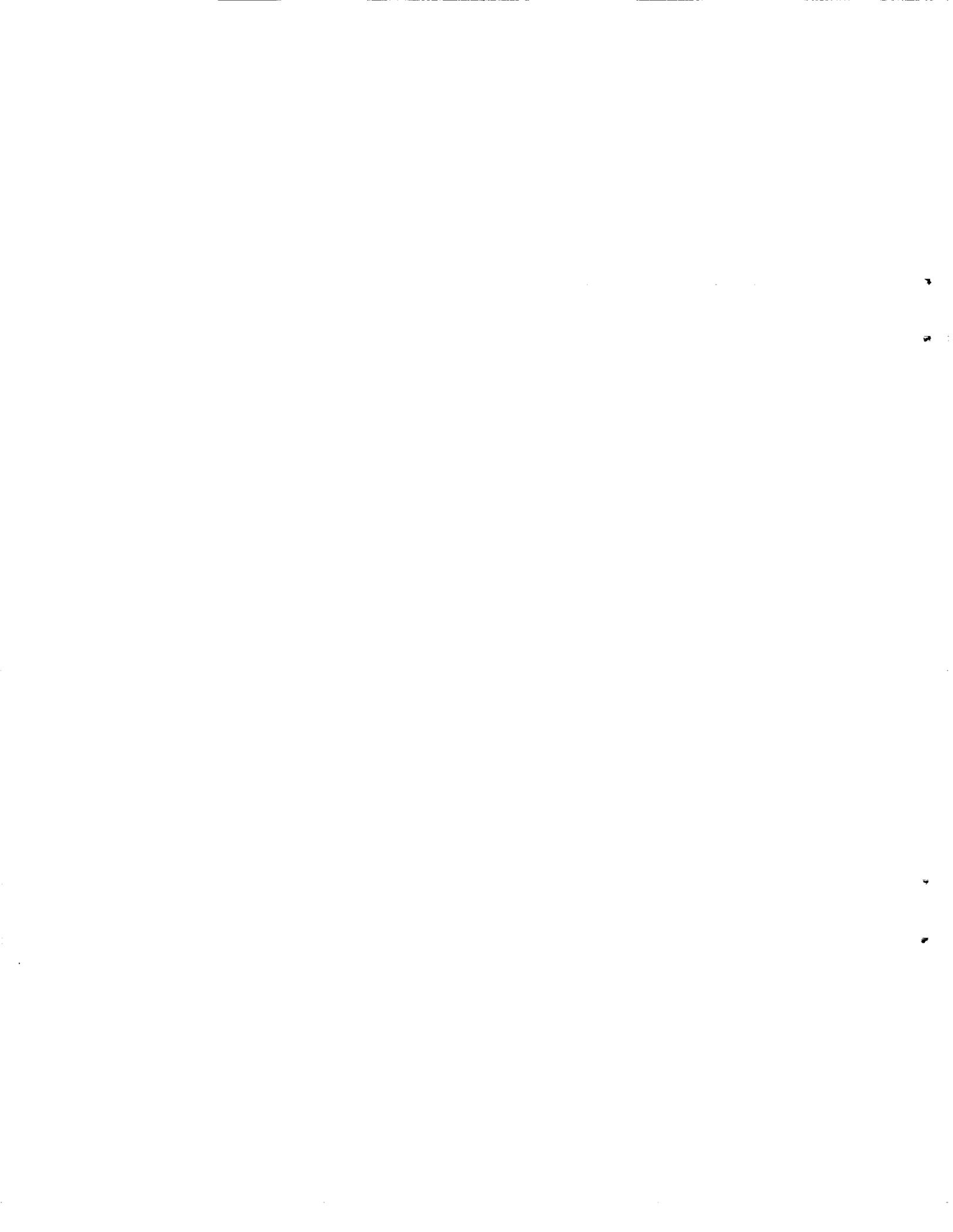
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**Session IV**



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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS



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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

**APC TENDENCIES HIGHLIGHTING : MANEUVERS DESCRIPTION**

- SYSTEMATIC MANEUVERS
- NON SYSTEMATIC MANEUVERS

**NEW TOOLS TO INCREASE MANEUVERS ACCURACY**

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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

**APC = PILOT HIGH GAIN**

- ⇒ UNEXPERIENCED PILOTS
- ⇒ STRESSFUL ENVIRONMENT:
  - final approach
  - formation flight
  - workload
- ⇒ CAPTURE AND FINE TRACKING TASKS:
  - altitude
  - heading
  - speed
  - roll
  - yaw

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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

SYSTEMATIC MAREIERS

**RUNWAY FLY OVER:**

The pilot must maintain a constant altitude and airspeed, and the aircraft aligned on the runway centerline

5 feet

V<sub>APP</sub>  
conf 3 or full  
gear down

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ALCANTARA

FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

SYSTEMATIC MANEUVERS

**SIDE STEP:**

In order to align with the runway, the pilot makes an aggressive side-step

V<sub>APP</sub>  
conf 3 or full  
gear down

400 feet  
to  
300 feet

100 m

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page 5

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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

SYSTEMATIC MANEUVERS

**LOW ALTITUDE AGGRESSIVE MANEUVERS :**

30°

500 feet  
to  
300 feet

100 m

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page 6

April 1999

**FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS**

**SYSTEMATIC MANEUVERS**

**ANALYTICAL MANEUVERS:**

$\phi=20^\circ$

$\theta=5^\circ$

Specific maneuvers defined to address precise areas of APC susceptibility

$\phi=20^\circ$

$\theta=5^\circ$

$\theta=20^\circ$

$\theta=5^\circ$

$\theta=5^\circ$

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page 7

April 1999

**FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS**

**NON SYSTEMATIC MANEUVERS**

**FLIGHT DISPLAYS:**

$60^\circ$

500 feet to 300 feet

CROWD

60° BANKED TURN

PRECISE CONTROL OF OVERFLY POINT

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page 8

April 1999

FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

NON SYSTEMATIC MANEUVERS

**FORMATION FLIGHT:**

Can be performed in many configurations, and not only in approach

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FLIGHT TESTING FOR APC : CURRENT PRACTICE AT AIRBUS

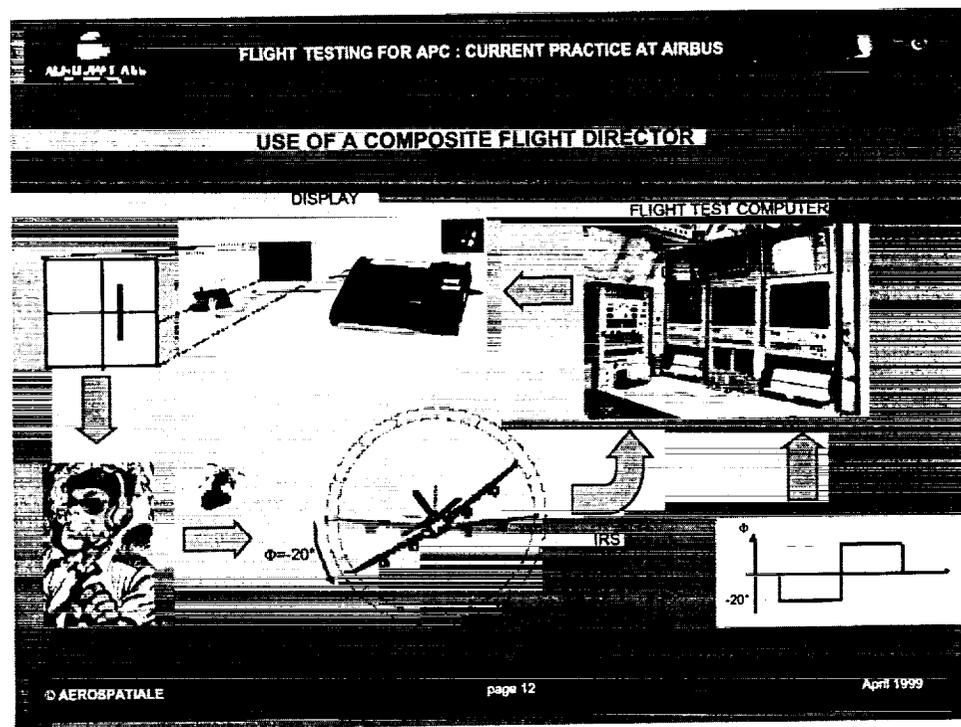
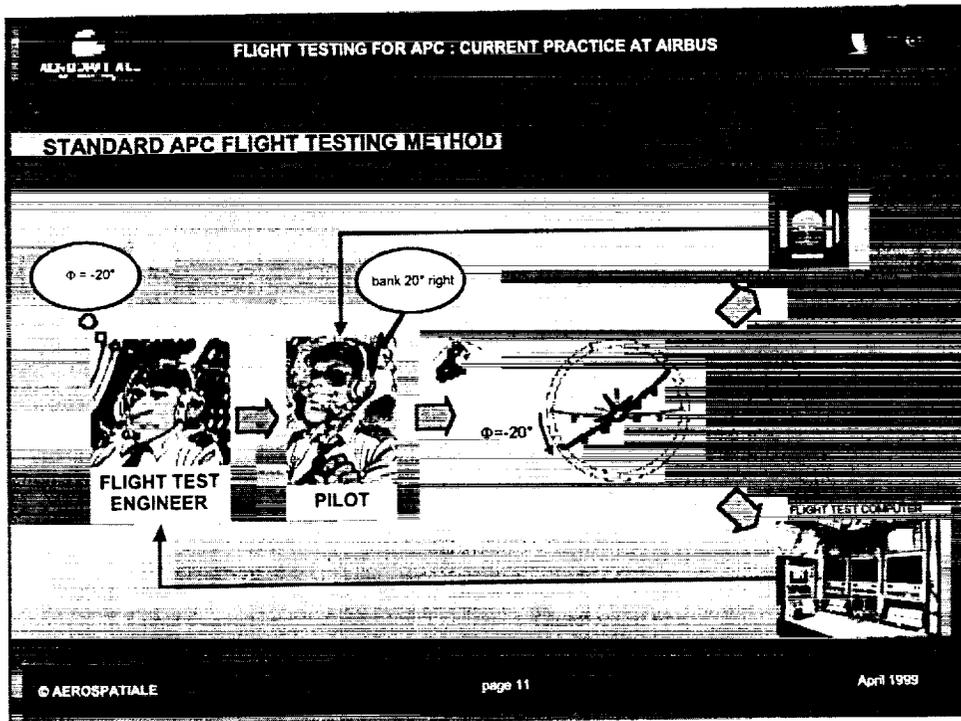
APC TENDENCIES HIGHLIGHTING : MANEUVERS DESCRIPTION

NEW TOOLS TO INCREASE MANEUVERS ACCURACY

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page 10

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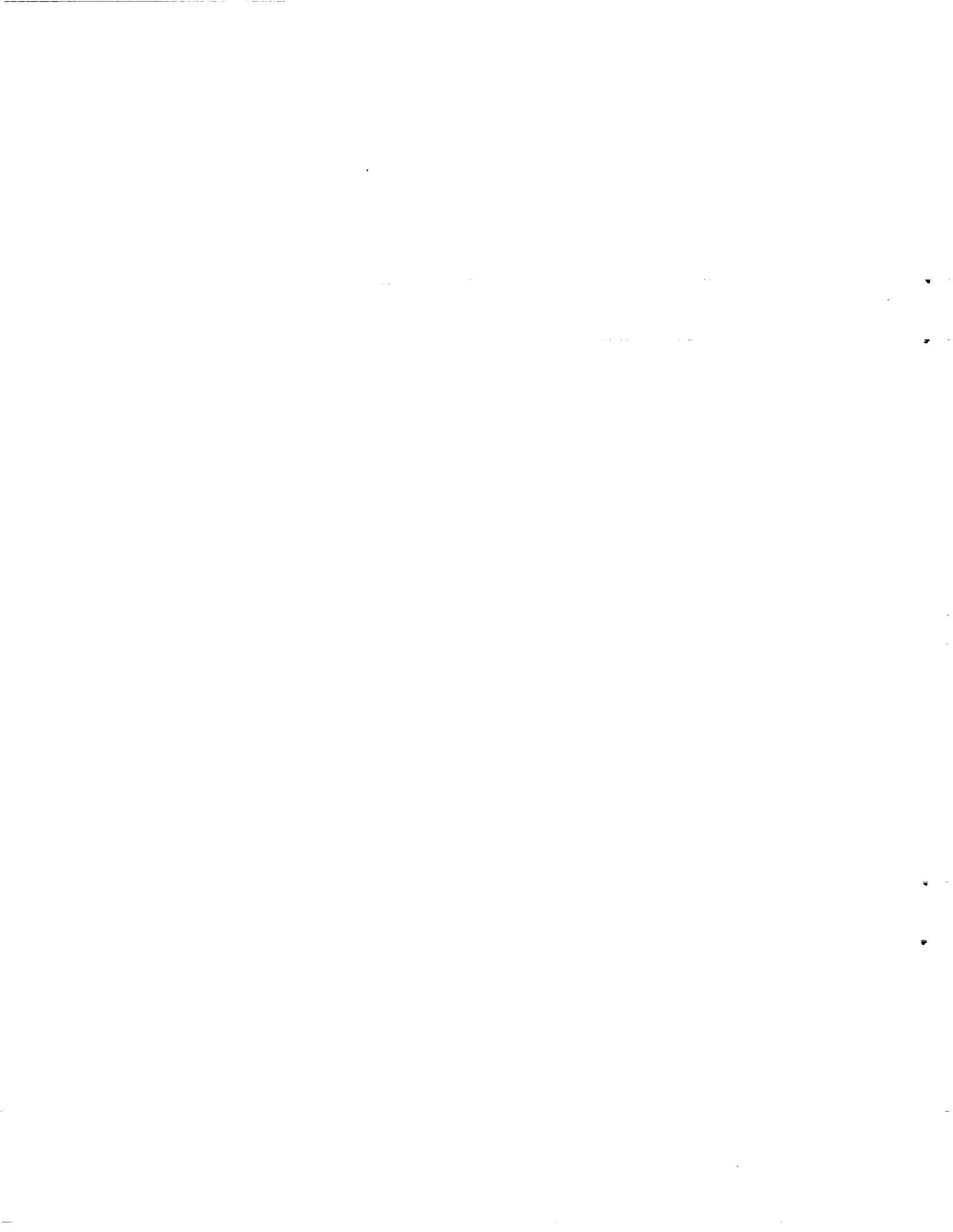
 COMPOSITE FLIGHT DIRECTOR ALLOWS ACCURATE MANEUVERS :

- both FD bars show  $\theta$  and  $\phi$  distance to targets
- enable any complex target (ramp, multi-sinusoid, pseudo random...)
- provide a wide range of analytical maneuvers
- cannot auto adapt (like a flight test engineer would do to trap the pilot)

 FLEXIBLE TOOLS :

- display delay can be adjusted
- FD bars can provide composite displays (use of many feedbacks  $n_z$ ,  $n_y$ ,  $q$ , ...)

 APC MARGIN SETTING LESS PILOT GAIN NEEDED FOR APC TESTING





# The Prediction and Suppression of PIO Susceptibility of Large Transport Aircraft

- An Evaluation of Proposed Methods -

Rogier van der Weerd  
Delft University of Technology / Aerospace Engineering  
Department of Control and Simulation  
6 April 1999

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This presentation is based on the results of a study more thoroughly reported in:  
*Weerd, van der R.; 'PIO Suppression Methods and Their Effects on Large Transport Aircraft Handling Qualities'; Thesis (M.Sc.), Delft University of Technology, Delft (The Netherlands), January 1999*

The study was carried out under a cooperative agreement between Delft University of Technology in the Netherlands and The Boeing Company at Long Beach. A student placement was made possible at the Stability, Control and Flying Qualities group of Boeing Phantom Works.

The project was carried out under supervision of:

The Boeing Company

John Hodgkinson

Dr. Edmund J. Field

Walter von Klein Jr.

Delft University of Technology

Prof.dr.ir. J.A. (Bob) Mulder

ir. Samir Bennani



## Contents

2

- Introduction
- Prediction of PIO
  - Available Criteria
  - Case Study Using Example Aircraft
- Suppression of PIO
  - Available Methods
  - Case Study Using Example Aircraft
- Conclusions and Recommendations

The study into PIO had two main objectives:

1. Investigate available methods for PIO prediction, including those recently proposed
2. Investigate possible remedies to PIO

Some of the group's expertise and experience with PIO could be used to evaluate and validate different criteria and methods using an example large transport aircraft with different configurations that have handling qualities that are considered well understood / investigated.



## Prediction of PIO

3

### Limitations of Linear Methods (Category I)

Most observed PIOs involved rate saturation of control surface actuator(s)

- Rate Saturation Result of PIO (poor Cat I properties)
- Or, Rate Saturation Actual Cause of PIO ?

Cat II Evaluation requires the inclusion of nonlinear behavior

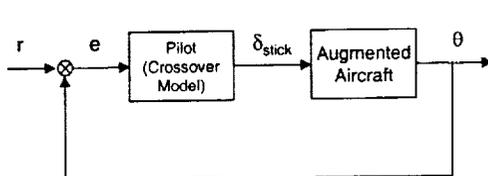
This can be done in

- Time Domain
  - Time Domain Neal-Smith
  - Hess Method for Nonlinear Dynamics
- Frequency Domain Using Describing Function Technique
  - DLR's Open Loop Onset Point (OLOP)



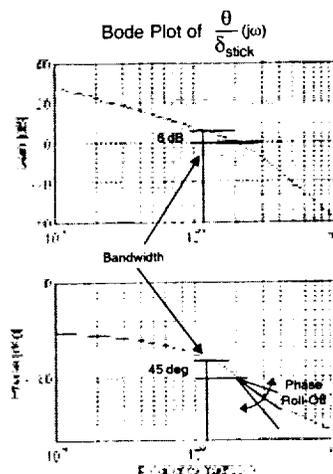
## Prediction of PIO Category I Example - Bandwidth

4



### Two Important Parameters

- Bandwidth Frequency,  $\omega_{BW}$   
("Speed" of System)
- Phase Roll-Off,  $\tau_p$   
("Predictability")



The Bandwidth criterion has been shown to be a well performing criterion on a wide variety of cases.

Extending Bandwidth to systems with nonlinear elements is possible (in fact, the method of performing a frequency sweep in order to estimate the system frequency response includes all kinds of nonlinear elements of the real system). Rate limiting elements in the command path of the EFCS can be identified easily for a given input amplitude. However, if the rate limiting element is part of a feedback loop, the identification of the describing function may fail, as typical nonlinear system behavior gets into play, e.g. the introduction of multiple equilibria (limit cycles, jump resonance).

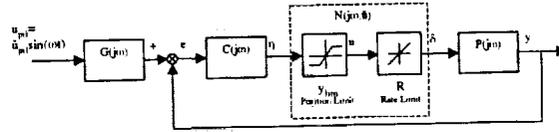
### REF

Hoh et al 1982.

Mitchell et al 1994

Mitchell et al 1998

# Nonlinear Systems (i)



**Limit Cycles** - sustained nonlinear oscillations, fixed amplitude, fixed frequency

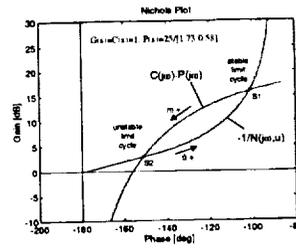
Conditions for a Limit Cycle are sought

Use neutral stability condition (Popov):

$$C(j\omega) \cdot N(j\omega, \hat{u}) \cdot P(j\omega) = -1$$

$$\Rightarrow C(j\omega) \cdot P(j\omega) = -\frac{1}{N(j\omega, \hat{u})}$$

$N(j\omega, \hat{u})$  is the sinusoidal describing function representation





## Nonlinear Systems (ii)

6

### Jump Resonance

No unique relation anymore between frequency and gain/phase of closed-loop response

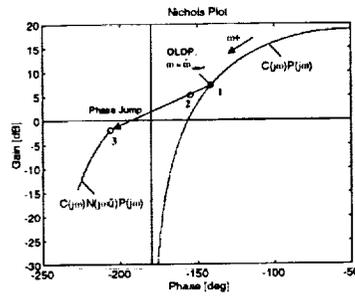
Phase Jump in Pilot-Vehicle System



Misadaptation by Pilot



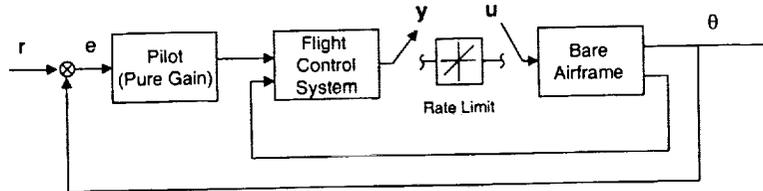
PIO





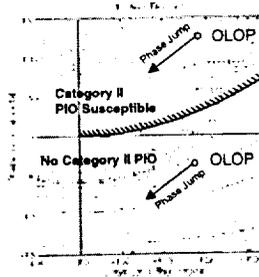
# Prediction of PIO Category II Example - OLOP

7



Rate limiting causes Jump Resonance  
OLOP determines "the consequence".

OLOP is  $L(j\omega) = \frac{Y}{U} (j\omega_{onset})$   
At the onset frequency



## REF

Duda 1997

Duda et al 1997



## Case Study Configurations Of The Example Aircraft

- Receiver Aerial Refueling Task
  - Clean Configuration
  - High Speed,  $M = 0.613$
  - High Altitude,  $h = 20,000$  ft
- Pitch Rate Command System Configurations:
  - Old Software Version F → PIO PRONE
  - Updated Software Version H → PIO FREE  
Added Phase Lags  $\tau_i = [0.1, 0.25]$
- Simplifications
  - Single Axis
  - No Model Uncertainties
  - No Structural Dynamics

### The Example Aircraft

High Performance Fly-By-Wire Military Cargo Airplane.

High-wing, four engines, T-tail configuration. Length 175 ft, height 55 ft, wingspan 170 ft, MTOW 600,000 lbs

'High gain' mission tasks include: Landing/Takeoff Short Austere Airfields and Aerial Receiver Refueling. PIOs were encountered during developmental flight testing for both tasks [1],[2]

### Configurations

Apart from configurations representing old and updated Electronic Flight Control System (EFCS) software versions, additional configurations were evaluated that represent the updated EFCS software with intentionally deteriorated characteristics.

The latter is accomplished by adding phase lags in the flight control system by increasing the time constant of a first order filter residing in the command path of the control laws.

### **REF**

Iloputaife et al 1996

Iloputaife 1997



# Pitch Axis PIO Event EFCS Software Version F

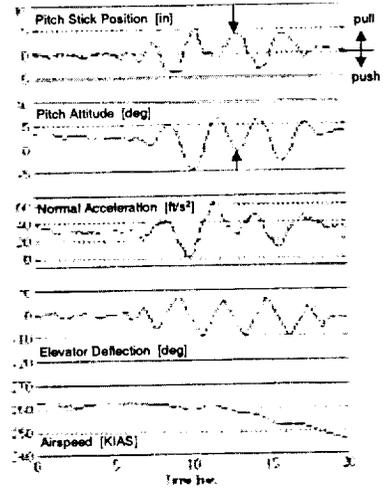
9

Pilot initiated emergency  
breakaway from tanker

Typical category II PIO:

- "High pilot gain"
- "Pilot is 180° out of phase"  
with pitch attitude
- Software rate limiting of  
elevator command signal

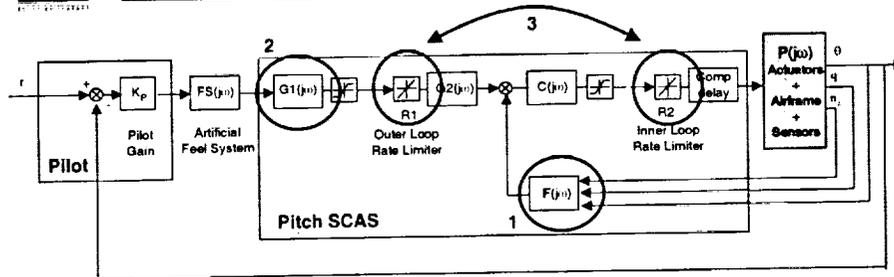
[ Ref. Iloputaife 1997, Iloputaife et al 1996 ]



## REF

Iloputaife et al 1996

Iloputaife 1997



Main differences between old and new software

1. Structural filtering optimization → increase system bandwidth
2. Stick shaping change → reduce control sensitivity
3. Change rate limits → fully use actuator capability

[ Ref. Iloputaife 1997, Iloputaife et al 1996 ]

## REF

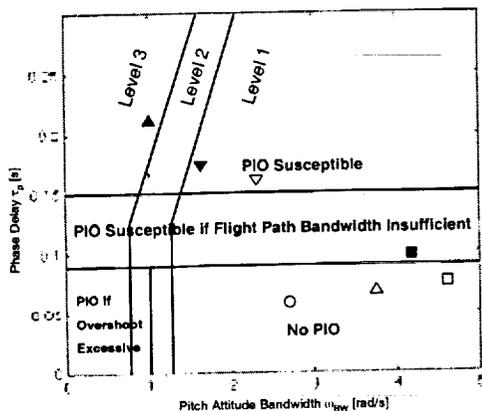
Iloputaife et al 1996

Iloputaife 1997



# Bandwidth Criterion Validation Using Example Aircraft

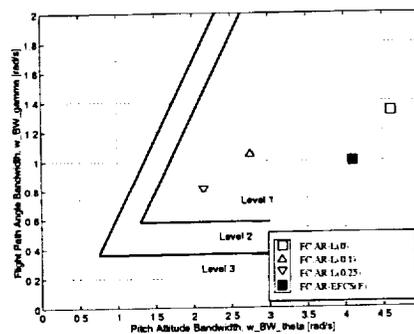
11



▲	PIO	B-2 <sup>*</sup> Approach	Flight Test
△	No PIO	B-2 <sup>*</sup> Aerial Refueling	Flight Test
▼	PIO	Space Shuttle <sup>*</sup>	Flight Test
▽	No PIO		
○	No PIO	X-15 <sup>*</sup>	Flight Test
■	PIO	Example Aircraft	Flight Test
□	No PIO		

\* Source: Klyde, D.H. et al 1995

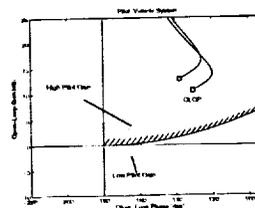
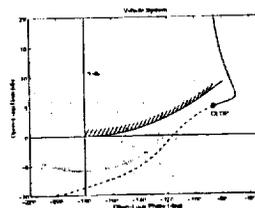
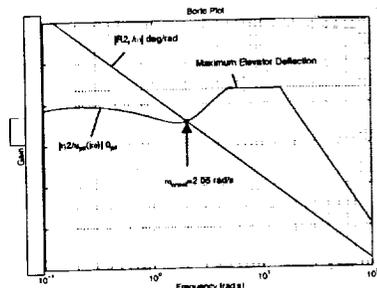
Criterion mapping is not considered to be successful discrimination since flight path bandwidth is sufficient for both configurations





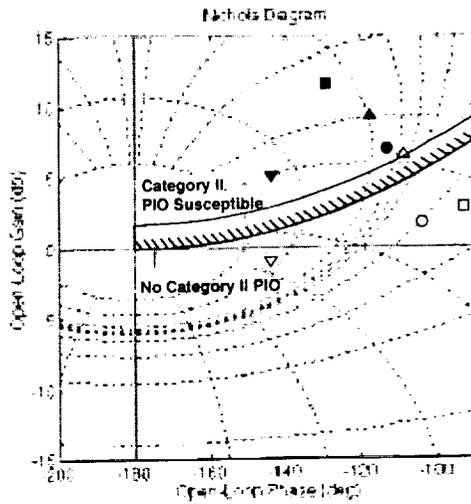
Onset Frequencies

Inner-Loop  $\omega_{onset}=2.05 \text{ rad/s}$   
 Outer-Loop  $\omega_{onset}=3.53 \text{ rad/s}$





# OLOP Criterion Validation Using Example Aircraft



▲	PIO	<b>Saab</b> * In-Flight Sim Experiment
△	No PIO	
▼	PIO	<b>Space Shuttle</b> * Flight Test
▽	No PIO	
●	PIO	<b>F-18</b> * Flight Test
○	No PIO	
■	PIO	<b>Example Aircraft</b> Flight Test
□	No PIO	

\* Source: Duda, H. 1997



# Results Comprehensive Criteria Validation

*Results Category I Criteria*

	LOES CAP	$\tau_0$	Bandwidth	Gibson	Smith- Geddes	Hess	Neal-Smith
FC.EFCS(F)	-/-	-/-	L1/no	-/no	-/no	L1/no	-/-
FC.EFCS(H)	L1/-	L2/-	L1/no	-/no	-/no	L1/no	L1/-

*Results Category II Criteria*

	Hess Nonlinear	OLOP	Time domain Neal-Smith
FC.EFCS(F)	<b>yes</b>	<b>yes</b>	<b>yes</b>
FC.EFCS(H)	<b>no</b>	<b>no</b>	<b>no</b>

**LEGEND**  
 L1,L2,L3 Predicted CHR  
 yes,no Predicted PIO  
 susceptibility  
 Criterion doesn't  
 include prediction

*Note: EFCS version F showed PIO tendencies  
 EFCS version H is the updated, PIO-free configuration*



## Remedy to PIO

### “Conventional” Methods

- Change Hardware
  - Actuators
  - Feel System Characteristics
  - Tail Size
  - etc.
- Change Control Laws
  - Control Allocation / Architecture
  - Control Sensitivity\*
  - Reduce Phase Lags / Filtering\*
  - System Bandwidth\*
  - Loop Gains\*
  - etc.

### “Alternative” Methods

- PIO Suppression Filter
  - Attenuate Pilot Command At Predefined Pilot Operating Conditions
- Software Rate Limiters With Phase Compensation
  - Reduce Phase Loss Under Rate Saturation

\* These methods were applied during the development of the example aircraft to fix the problems

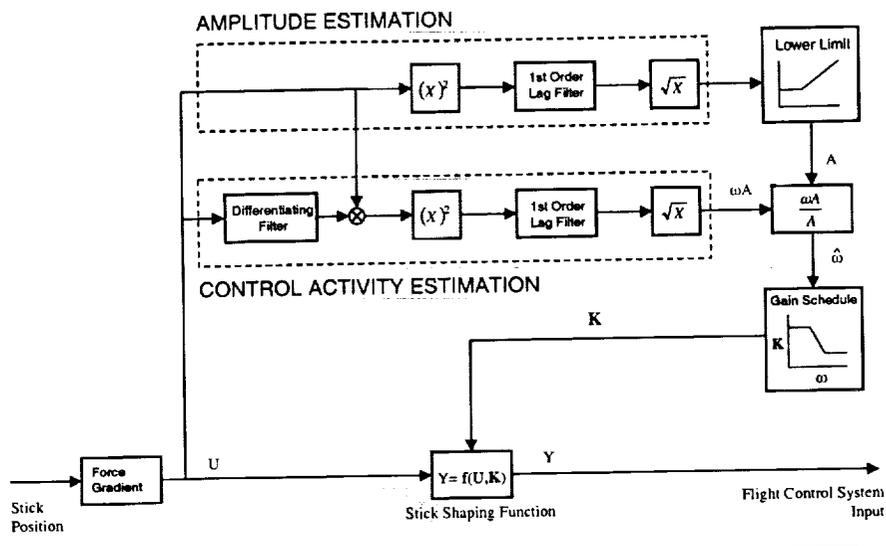
On most cases of PIO experienced in the past, the problems were discovered in a relatively late phase of development, or even, during routine operation. A solution that allows the established control law structure to remain the same while eliminating PIO susceptibility surely is preferable.

Goal: Look for methods that solve the PIO problem without having to redesign control laws.



# PIO Suppression Filter Initial Design

17



REF

Powers 1981



## PIO Suppression Filter Functionality

18

Stick shaping function usually is a 3<sup>rd</sup> order polynomial:

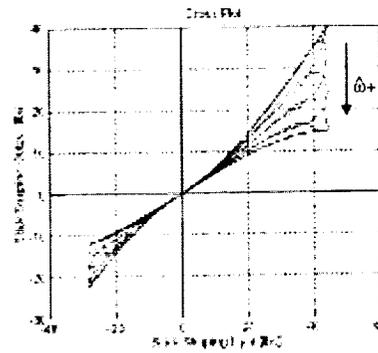
$$Y = u ( k_1 + k_2 \cdot |u| + k_3 \cdot u^2 )$$

Suppression is obtained through:

$$Y = u ( k_1 + k_2 \cdot |u| \cdot K + k_3 \cdot u^2 )$$

In which **K** is The suppression gain

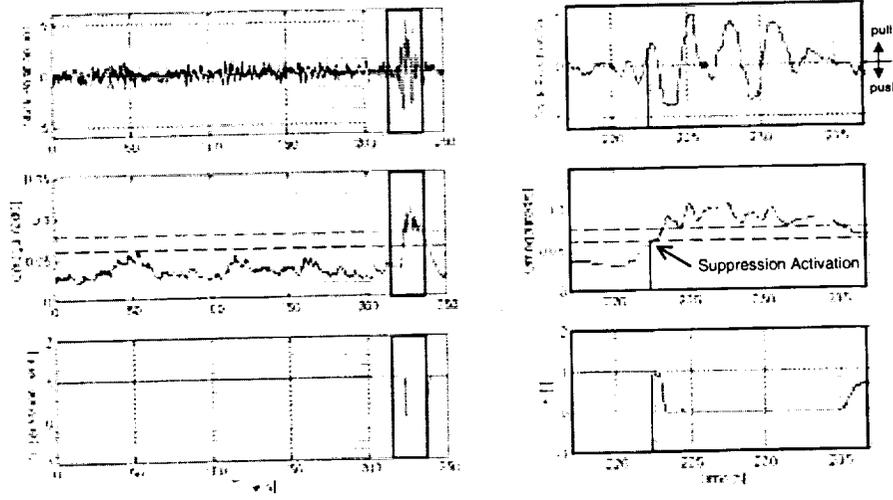
"Stick desensitizing"





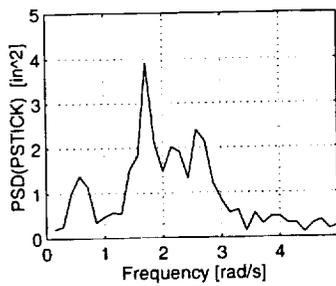
# PIO Suppression Filter Response to Example Case

19

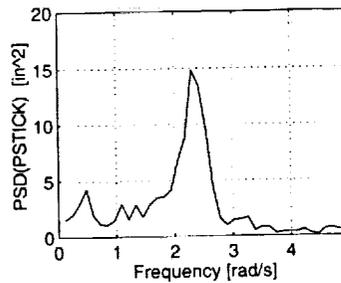


[ Source Ilputaife 1997 ]

## PSD of Stick Deflection Signal



Excluding PIO Frame



Including PIO Frame

Sampling Rate

$$f_s = 10 \text{ Hz}$$

No. of Samples

$$N = 2,300$$

Frequency Resolution

$$\Delta\omega = 0.14 \text{ rad/s}$$

Conclusion:

During 'normal' task execution, pilot inputs contain energy in the frequency region of the actual PIO (which is about 2.3 rad/s)

REF

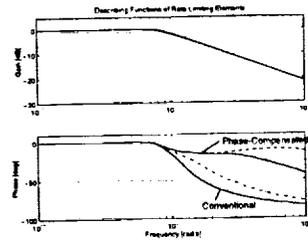
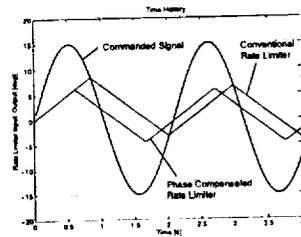
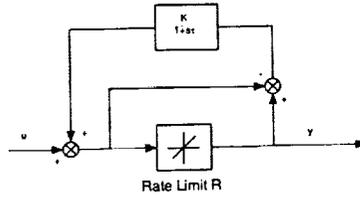
Ilputaife 1997



# Phase Compensated Rate Limiting Schemes<sup>20</sup> (Rundqwist - Saab Military Aircraft)

**Concept:**

- Under rate saturation, excess in demand is fed back
- Rate limiter command signal is attenuated
- Result: Output will change direction when input does



**REF.**

Hanke 1995

Rundqwist et al 1997



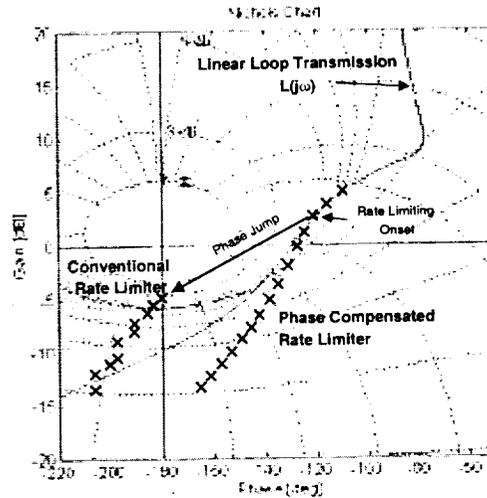
# Phase Compensated Rate Limiting Schemes<sup>21</sup> Effect on Closed-Loop System Using OLOP

## Stability Margin Analysis

Conventional rate limiting:  
Phase Jump, undesirable

Alternative rate limiting  
Avoids Phase Jump

*Retain stability with same rate limit imposed on system*





## Conclusions

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- Category II PIO criteria were successfully validated against a limited selection of example aircraft configurations
- When designed properly, a PIO suppression filter can identify a developing PIO And take avoidance action.
- Phase compensated rate limiters can alleviate the severe penalty associated with rate saturation in a closed-loop system.



## Further Work

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- Perform similar analysis for other PIO data
- Compare results of this study with recent experimental flight test data
- Address effect of structural dynamics on handling qualities and PIO
- Incorporate modern tools for stability analysis ( $\mu$ , LMIs)  
Goal: towards category III PIO prediction



## References

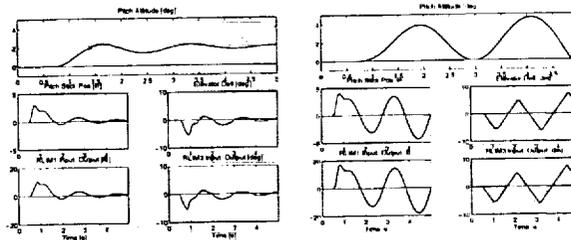
24

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- Bailey, R.E., Bidlack, T.J.:** 'A quantitative criterion for Pilot-Induced Oscillations: Time Domain Neal-Smith Criterion'; AIAA-96-3434-CP
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- Hoputaife, O.I.:** 'Minimizing Pilot-Induced-Oscillation Susceptibility during C-17 development'; AIAA-97-3497.
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- Powers, B.G.:** 'An Adaptive Stick-Gain to Reduce Pilot-Induced Oscillation tendencies'; Journal of Guidance, Control and Dynamics, Volume 5, Number 2, 1981.
- Rundqwist, L., Hillgren, R.:** 'Rate Limiters with Phase Compensation in JAS 39 Gripen'; SAE Aerospace Control and Guidance Systems Committee, Monterey, CA, March 1997.



## Backup Slide Results TDNS Criterion

25



Time Domain Neal-Smith Response for  
Software Version H. Acquisition Time  
 $D=1.4$  seconds.

Response for Software Version F.  
Same Conditions

Discrimination between good and bad configurations lies in  
Acquisition Time  $D$  for which system grows unstable.

Software Version H allows a smaller acquisition time

Criterion definition doesn't yet provide clear boundaries for  $D$

REF

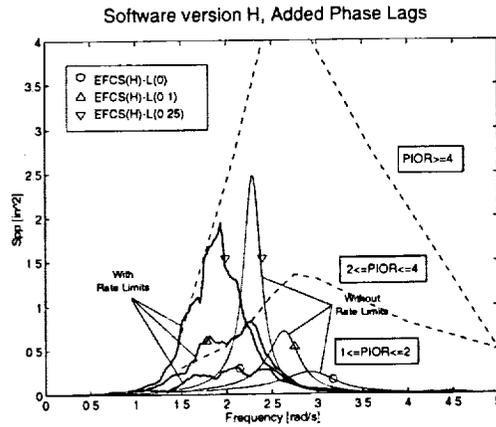
Bailey et al 1995, 1996



# Backup Slide Results Hess Nonlinear (i)

- Resulting Hess mapping for
- Linear system
  - Active rate limiters

(Note: Mapping for Software version F (old) is not plotted; it results in an unstable system, caused by excessive rate limiting)



## REF

Hess 1989, 1997<sup>a,b,c</sup>, 1998

Hess et al 1998



## Backup Slide Results Hess Nonlinear (ii)

27

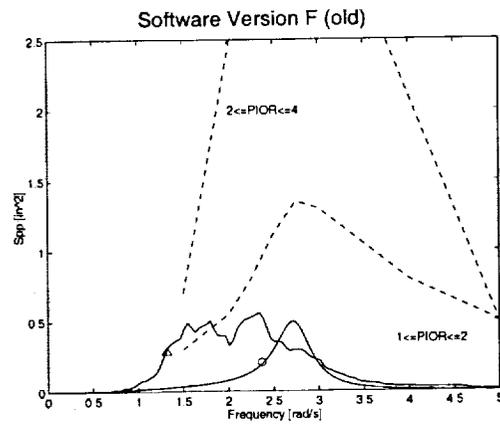
### Phase Compensated Rate Limiting Schemes Effect on Closed-Loop System Using Hess

#### Application of Hess method

Linear Hess mapping yielded  
solid PIO-free prediction

Inclusion of conventional rate  
limiter drove pilot-vehicle  
system unstable

System with phase  
compensated rate limiters is  
stable, but not predicted solid  
PIO-free (boundary has not  
been thoroughly validated)





# Flight Testing for PIO

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## Introduction

- Theory reduced to practice
- Developed intermittently over 32 years
- Highly nonlinear process
- Theory applied to numerous aircraft cases at EAFB since 1975
  - Several PIO predictions prior to flight test
  - Two non-PIO predictions
- Incorporated into TPS curriculum since 95B

## Priorities

- Solve the airworthiness problem
  - Eliminate safety-of-flight issues related to PIO
    - PIO sensitivity training
    - Proficiency training
- Let the subsystems people deal with Cooper-Harper ratings and psycho-babble
  - Performance definitions are negotiated items
  - Workload is indefinable

## A Question:

- No self-respecting engineer would design a servomechanism using criteria that are routinely accepted for piloted control of airplanes.
- Why should a FCS be designed to less stringent criteria than a floppy disk drive servo?

## The Process

- Predict/Test/Verify
  - Characterize the Expectation
  - Exercise Experimental Technique
  - Understand the Results

## Predict

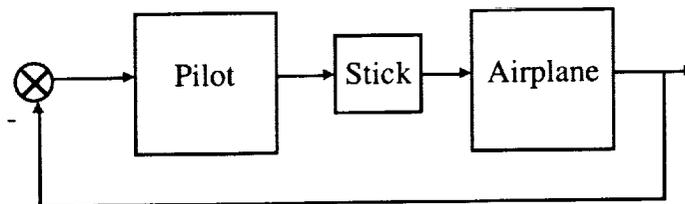
- Theory or Criteria
  - Smith-Geddes (implemented in the RSMITH software)
- Simulation
  - Simulate what?
    - HQDT

## Aside: Definition

- PIO is pilot-in-the-loop oscillation
- PIO generally refers to pilot-in-the-loop instability

## Aside: Characterizing PIO

- PIO due to excessive phase lag in the airplane
- PIO due to excessive command gain (stick sensitivity)



## Aside: Phase-Gain Interaction

- The RSMITH software was written to account for the interactions
  - Predicts CHR for worst-case tracking
  - Predicts max stick sensitivity to avoid PIO

## Aside: Stick Sensitivity

- The dominant HQ parameter
  - Overrides phase-based criteria (including Smith-Geddes)
- Typical airplane:
  - Stick sensitivity for no-PIO = insufficient authority to maneuver
  - PIO susceptible
  - Non-FBW transports are possible exceptions

## Testing for PIO

- No Phase 3 (Cooper-Harper) testing
- HQDT -- the only maneuver that works
  - A sufficient criterion for PIO
  - Go/No Go engineering criterion
    - Closed loop task
    - Divergence = PIO susceptibility
    - Convergence = Not PIO susceptible
    - Task is not a factor
    - No Cooper-Harper ratings, no performance standard

## Aside: HQDT

- Unnatural act
- The old guys hate it
- The new guys have trouble with it
- Has a theoretical basis: sufficient condition for PIO
- T-38 experience: proof that susceptibility does not equal unsuitability

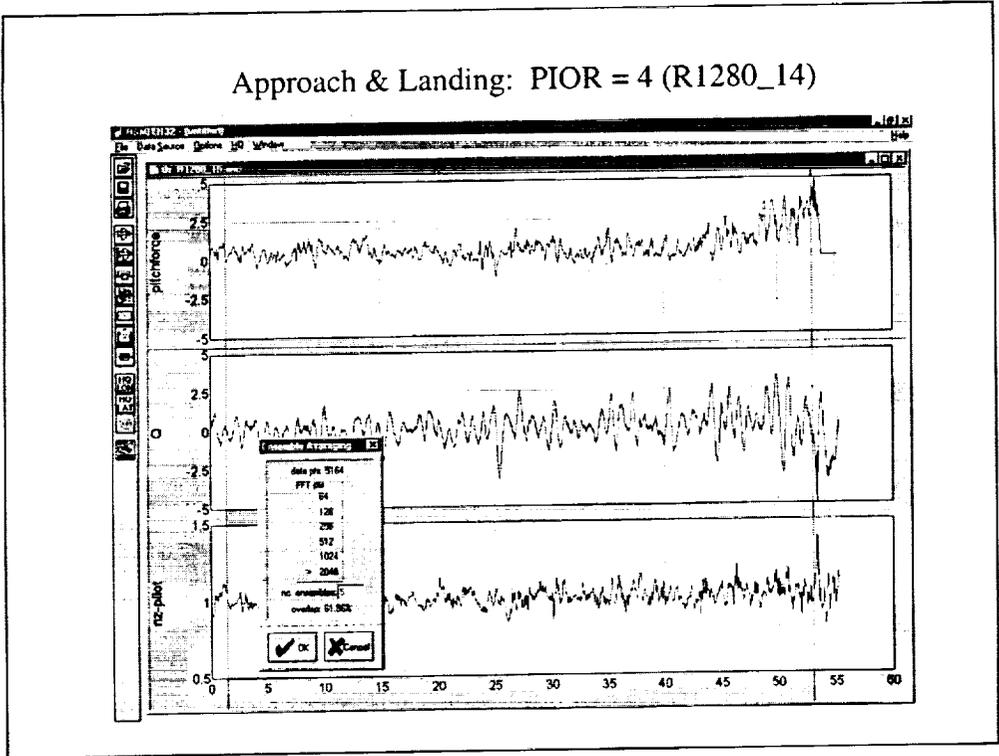
## Understanding the Results

- Priority: Verify that you tested what you thought you tested
- Identification of aero parameters
- Model the FCS + airframe
- Freq response analysis of flight data to confirm model validity
- Write a tech report based on fact, not expectation

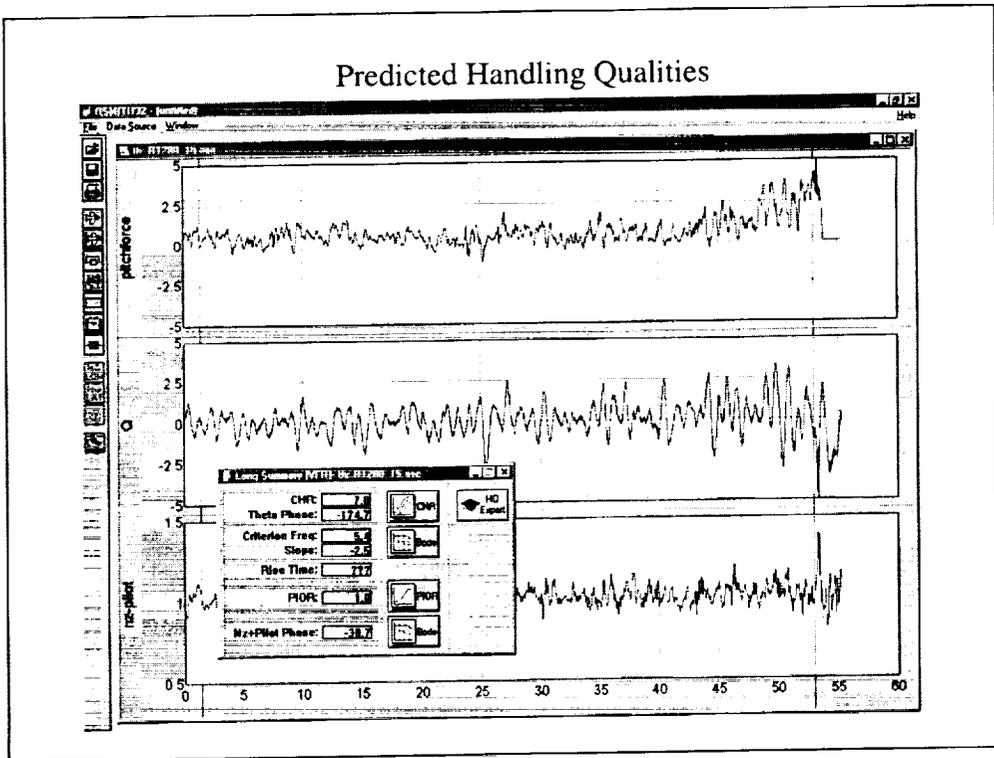
## Case History

- Approach & landing task
- Control laws designed to satisfy Smith-Geddes criteria using RSMITH program
- Predicted Level 1
- Flight test: Level 2/3
- Initial reaction: failure of criteria
- Fact: Invalid aero model and VSA mech; criteria worked

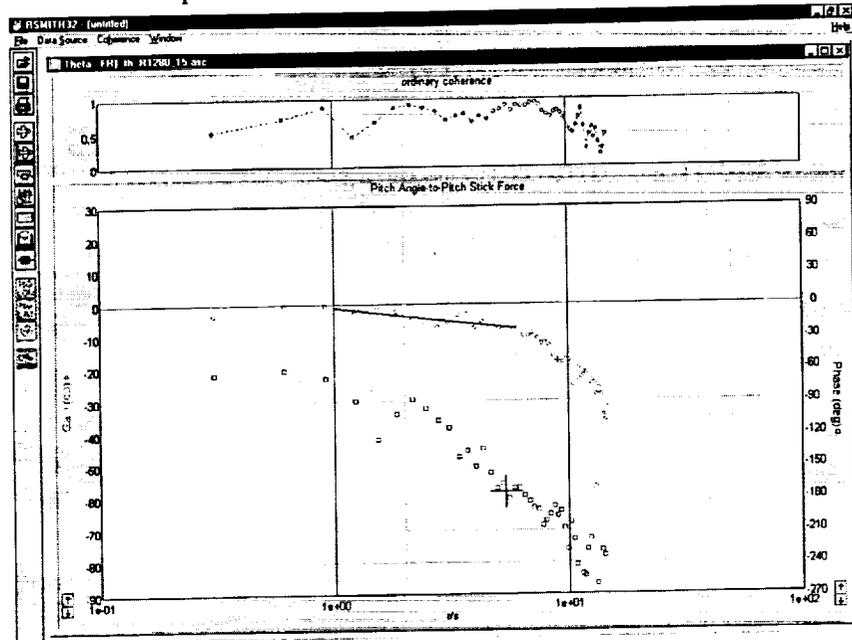
### Approach & Landing: PIOR = 4 (R1280\_14)



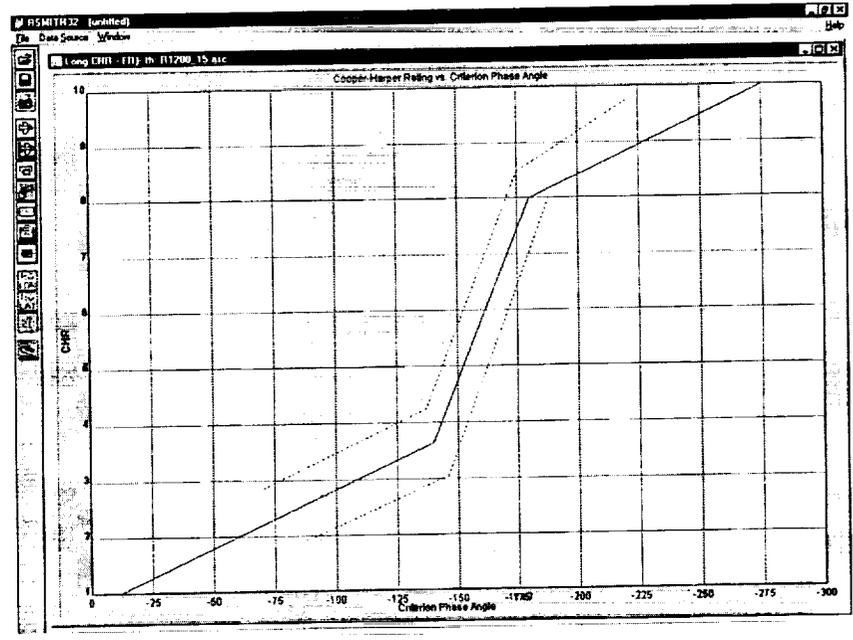
### Predicted Handling Qualities



## Slope Parameter & Criterion Phase Angle

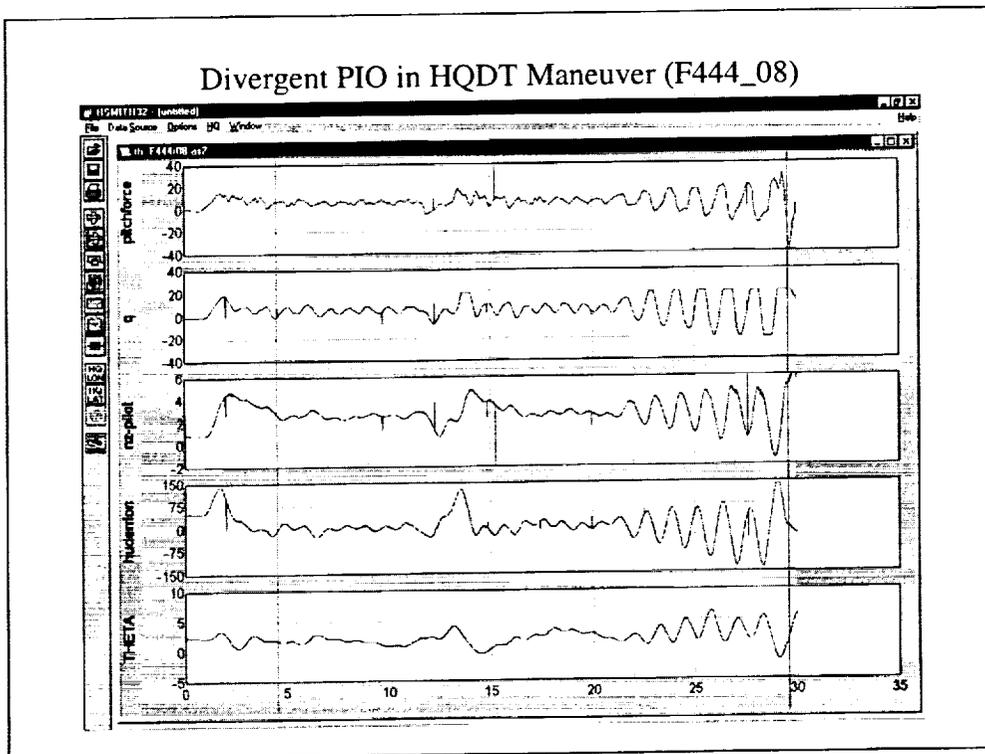


## CHR vs Criterion Phase Angle



## Case History: HQDT

- HUD tracking task, simulated air-to-air
- PIOR = 5
- Phase 3 tracking: CHR = 8/7/6/5/7
- Phase 3 tracking: PIOR = 5/5/3/3/3



**Use of In-Flight Simulators  
for PIO Susceptibility Testing and for  
Flight Test Training**

By

Michael Parrag  
Veridian Engineering (Calspan)  
PIO Workshop  
Dryden FRC, Edwards, CA  
April 1999

The common denominator for both developmental testing and  
flight test training



Realistic task in a realistic environment with uncompromised  
visual and motion cues

Before talking about the in-flight simulator "tool" in the PIO context let me say a few words about PIO phenomenon from a piloting viewpoint - having endured many as an evaluation pilot on research programs and having witnessed hundreds as a not so casual observer or safety pilot in a number of our in-flight simulators

I would like to briefly review several aspects of the PIO phenomenon:

- The variety of pilot input → aircraft response features that cause unpredictability, a root causal factor in PIO's
- The pilot's way to characterize a PIO in terms of how it affects this piloting task
- The circumstances that may trigger PIO events.
- Using the understanding of the above factors to structure flight test methodology oriented at uncovering PIO susceptibility
- Finally, this will lead to how the in-flight simulator is a safe and cost effective tool to accomplish flight test objectives

## Response Unpredictability

Primary causal factor for PIO



Response Unpredictability

Predominantly a situation where initial response to pilot input  
miscues pilot as to where response will end up

or

pilot simply does not get expected response for a given input

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## Potential Sources of Unpredictability

• Very initial response

- time delay

- onset rate

too high

too low

• Mismatch between time to first perceptible  
response and response buildup

• Steady state sensitivity

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## Potential Sources of Unpredictability (Cont.)

- Poor correlation between pilot sensed responses

e.g. pitch rotation vs 'g' buildup (in up and away flight)

or

pitch attitude and flight path angle (in P.A.)

- Dominant cue creating unintended loop closures (synchronous behavior)

e.g. effects of  $n_{z_p}$  and  $n_{y_p}$

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## Potential Sources of Unpredictability (Cont.)

- Non linear effects

- large and sharp (sudden) changes in characteristics such as in command gain scheduling

or

in response characteristics

Mechanical Non-Linearities

- rate limiting in surface actuators or in software along command path

- Control misuse with exotic FCS modes

or

when intuitive pilot behavior can get you in trouble

- Excursion into non-linear aerodynamics

- hi alt/hi Mach - pilot vehicle motions venture into Mach buffet or stall buffet

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## Potential Sources of Unpredictability (Cont.)

- A major design culprit



- Overaugmentation

- excessive FCS gains in name of "robustness" or "agility"

## Potential Sources of Unpredictability (Cont.)

- Some outcomes:
  - overly abrupt dynamics in pitch/roll
    - causes staircase input/response in gross acquisition and causes hi freq/low amplitude PIO in fine tracking (bobbles)
  - requires use of more sensor filtering → time delay
  - drives rigid body dynamics closer to aeroelastic modes structuring filtering → time delay
  - hi fb + hi command gains → rate saturation more likely
  - often worse in turbulence
  - unnecessary wear/fatigue on actuators, surfaces and associated structures

## Potential Sources of Unpredictability (Cont.)

- Another major design culprit → FCS complexity
  - designer cannot anticipate all possible interaction between FCS and pilot
  - ∴ cannot guarantee “PIO free”

## Types of PIO



Pilot's Interpretation  
based on how PIO  
interacts with task

## Types of PIO (Pilot's Interpretation)

- PIO's have two distinguishing features namely, frequency and amplitude, that determine how the pilot can deal with PIO in context of a task

### Examples

- Hi freq, low amplitude such as in roll with very short  $\tau_R$



### roll ratcheting

- excessive  $p$  causes significant  $n_y$ , which cause rapid reversals by pilot - settles into "dominant cue/synchronous behavior"
- viewed by pilot as very annoying but task remains controllable; pilot can easily judge average of PIO's

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## Types of PIO (Pilot's Interpretation) (Cont.)

- Low freq., larger amplitude —→ often seen with rate limiting

· pilot is unable to judge average of oscillations

· generally not controllable if task constraints do not permit pilot to back out

- Medium frequency —→ gray area; degree of problem caused in task depends on:

· amplitude of PIO

· how much he is "driven" by a dominant cue

· whether pilot can manipulate "average" to continue task

· personal piloting technique - can pilot tone down his inputs?

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## Circumstances which may "trigger" PIOs

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## Circumstances which may "trigger" PIO's

1. Found accidentally in an aggressive or high precision task scenario when undesirable aspects of the Pilot-Vehicle System and/or environment come in coincidence or change unexpectedly
  - major objective during development should be to minimize risk of this
2. Uncovered during flight test by a determined and disciplined process of exploration and discovery
  - utilizing high gain tasks under demanding environmental conditions
  - process intended specifically to prevent "accidental" discovery of PIO where consequences are generally more serious
3. In both cases, pilot demands rapid response and precise performance

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## Circumstances which may "trigger" PIO's

- In the course of a high gain task scenario, when one or more undesirable elements influencing the Pilot-Vehicle System closed loop performance surface unexpectedly
  - In general, when sudden or anomalous changes occur in pilot behavior, effective vehicle dynamics or in feedback to the pilot
  - Atmospheric upsets such as:
    - turbulence
    - cross wind
    - wake turbulence
    - wind shear

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## Circumstances which may "trigger" PIO's (Cont.)

- FCS mode change during a high gain task
  - esp. with significant change in [A/C + FCS] dynamics, trim change or FCS dead time
- Mode change with gear/flaps or air/ground switch or unexpected FCS mode due to erroneous input from aircraft sensors
  - e.g. FCS gains for wrong flap deflection
- Mixed manual and auto FCS modes when intuitive behavior mixes with auto control law to give unpredictable response
  - e.g. auto compensation for engine out - - - creating control problem when pilot does get in loop

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## Circumstances which may "trigger" PIO's (Cont.)

- In course of low gain monitoring tasks (pilot out of loop), sudden change:
  - Surprise (shock) - startle effect
    - "hours of boredom punctuated by seconds of sheer panic"  
sudden entry into control loop due to upset or change in pilot's perception → often results in much bigger correction than needed
      - e.g. akin to sudden awareness after dozing off at the wheel of a car
  - unexpected actuation of some a/c configuration device such as auto speed brakes, L.E. slats
  - system failure → e.g. runaway trim, sensor or display failure

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## Circumstances which may "trigger" PIO's (Cont.)

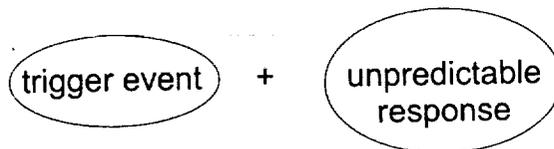
- Upset after "hidden onset" e.g. autopilot becomes saturated by turbulence upset, hinge moments due to ice - - - then "lets go";
  - pilot is faced with out of trim upset
- above scenario but under conditions where handling qualities are marginal + close to aircraft limits
- lack of "situational awareness" leading to inappropriate interaction between pilot and automatic systems
- "pilot and copilot fighting each other" - - - on the controls

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## Circumstances which may “trigger” PIO’s (Cont.)

### In Summary



PIO is outcome of the latter only or both

## The Determined “PIO Search” Flight Test Process

- Objective is to minimize risk of PIO occurrence in operational use
- Need to find the “black holes” in flight test - military testing - civil certification

## To ensure coverage of vast set of circumstances in which PIO's can occur

Need to test in combination:

- All potential [aircraft + FCS] modes/configurations
  - low probability of occurrence is not excuse not to test
- Relatively extreme environment conditions - progressively but sufficiently early
- Aggressive yet high precision tasks
- Clever introduction of "trigger events" described previously - to reproduce surprise and stress to force "unusual control inputs"

**This is difficult to implement!**

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## Elements of rigorous/determined PIO search process

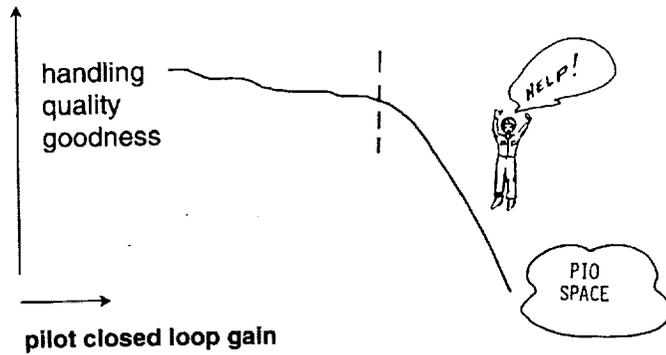
- High gain tasks
  - need to work high frequency portion of PVS to experience phase lags associated with many initial response problems
  - $t = 0^+ \Rightarrow$  high freq
- Unfavorable atmospheric conditions
- Secondary task loading
- Piloting technique
- Urgency of control action
  - maybe combined with triggers?
- State of pilot's situational awareness

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Must pay careful attention to these process elements because dealing with flying quality CLIFF



GOING OVER IS SENSITIVE TO PROCESS ELEMENTS



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## TASK

- PA → Approach  
VS  
Flare and Touchdown  
Lake Bed vs Runway!  
vs Carrier
  
- UP AND AWAY → Formation  
VS  
A/A Tracking  
VS  
A/A Refueling

Need Tight (Demanding) Task for Proper Discrimination!



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## Closed-Loop Standards of Performance

- Well Defined Predetermined Standards for  
Desired Performance  
Adequate Performance  
  
e.g. in terms of mil errors for tracking or  
touchdown box on runway
- Ensure that pilots are proficient in mechanics of task

## Environmental Factors

- Turbulence including gust upsets
- Cross-winds
- Day-Night; - VFR - IFR  
i.e. Visual Cues
- Secondary Task Load

## Pilot Closed-Loop Gain

- **Aggressiveness** in Task
  - Operationally Realistic
  - Pilot Chooses ! can back out!
- **"Pucker Factor"** - - - Forced On Pilot by Environment/task constraints
  - PIO's ARE NOT Optional

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## Representative Piloting Technique

- Aircraft needs to be PIO safe for entire piloting population
- Piloting population is not uniform
  - There are low gain predictive types
  - There are high gain "ham fisted" types
- Both types need to be covered in PIO search, but especially latter
- Should also include:
  - Pilot unfamiliar with particular aircraft being tested, unbiased first opinions can be very telling
  - Test pilots who have experienced PIOs in past and who can effectively communicate their evaluations

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## Urgency of Control Action

- Need to brief pilots:

- to initiate aggressive gross acquisition
- about compelling and immediacy to recovery from upset
- “time to acquire” is the critical element

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## State of Pilot's Situational Awareness

Situational Awareness (S.A.) —→ Pilot being fully cognizant of current aircraft state (configuration, FCS mode, autopilot mode etc.), of appropriate control strategy, or of his environment (weather, other aircraft)

Lack thereof or sudden change in S.A. may generate trigger or otherwise cause an “inappropriate” control input

may be related to workload, understanding of FCS modes, piloting technique etc.

– consideration of the above possibilities needs to somehow be worked into the test plan

e.g. doing “blind” tests when safely feasible

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PRD WorkShop 01, Page 49/1899

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## Tools of Pilot-in-the-loop Tests

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PIO Workshop/MI, Paris April 1999

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## With Current New Technology - - FBW Aircraft

- Reliance on predictive analytic metrics  
Inadequate for handling qualities
- Pilot-in-the-loop evaluations essential

Flight Research Group  
PIO Workshop/MI, Paris April 1999

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## Pilot-in-the-Loop Evaluations

- Only means of integrating all dynamic elements in closed loop

Pilot

Controllers/Feel System

A/C + FCS

Displays

Weapon Systems

In context of mission-oriented tasks

- Only credible means of assessing handling quality goodness and minimizing risks of hidden "cliffs"

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PRO Workshop/ML: Paragon/1999

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## Tools of Pilot-in-the-Loop Evaluations

- Ground-Based Simulators
- In-Flight Simulators
- Prototypes
- Operational Vehicles

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PRO Workshop/ML: Paragon/1999

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## Tools of Pilot-in-the-Loop Evaluations

### Ground Based Simulators

■ Considerations:

- Readily available at design site
- Serves key role in developmental evolution of dynamic elements
- Limitations:

Fidelity of synthetic visual and motion cues

worst in conditions where many current FCS problems erupt

Task environment → control strategy (can be quite different from flight)

Lack of real flight stress

## Tools of Pilot-in-the-Loop Evaluations (Cont.)

- History indicates that for demanding high-gain tasks, ground based simulation has often been misleading - failed to expose dangerous problems

## Tools of Pilot-in-the-Loop Evaluations (Cont.)

### ■ In-Flight Simulators (IFS)

- Visual and motion cue environment correct/real, not synthetic
- Real flight stress
- Real piloting tasks

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## Tools of Pilot-in-the-Loop Evaluations (Cont.)

### ■ In-Flight Simulator (Cont.)

- Limitations
  - If IFS Not 6 DOF → some cues may not be fully representative
  - A number of scenarios outside capabilities of currently operational IFS's.  
e.g. in high  $\alpha$  etc.
  - Only as good as model
- However, for a given "model" → gives most credible handling quality answers
- Generally much more credible effects of turbulence than in ground sim

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## Objectives of IFS

- Verify/check ground sim results in real flight environment
- "Calibrate" ground simulator
  - Test pilots become tuned how to better use it for credible results given its particular cueing limitations.
- Historically has brought small dedicated problem-solving oriented flight test team together
  - Fostered communication

Pilots ↔ Engineers ↔ Managers

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P/O Workshop/MLI, Para 4/1999

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## Tools of Pilot-in-the-Loop Evaluations (Cont.)

### Prototype Vehicle

- Very Costly Tool
  - economically and from schedule viewpoint
- High risk environment in which to test potentially questionable or unknown characteristics
- High Cost and Risk Tool in which to test modifications/fixes

### Operational Vehicle

- Once a vehicle is operational problem, fixing is a major fiasco

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## Test Pilot Evaluation Tools

- Flight Test Tasks/Techniques
- Communication Tools

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PID Workshop 4.1 Per April 1999

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## Flight Test Tasks

### “Real” Tasks

- Using no special displays
- Single element or combination of elements from an operational scenario
  - pitch or roll attitude captures
  - 45° bank level (const. altitude) turns with aggressive reversal
  - Close formation flight
  - Air to Air Tracking
  - Probe and Drogue refueling task
  - Offset landing approaches
  - aggressive alternate tracking of runway edge @ 100 ft AGL (or altitude safely appropriate for particular aircraft size)

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PID Workshop 4.1 Per April 1999

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## Flight Test Tasks (Cont.)

### Synthetic Tasks

- Tracking task presented on a convenient pilot display such as:

HUD (Head Up Display)  
MFD (Multi Function Display)  
Attitude Director Bars

- or presented on a removable LCD display with tasks preprogrammed on a P.C. computer (demonstrated in Learjet)

- Tasks must include single axis and combined axes elements with sufficient frequency and amplitude content on the tracking bar to test for PIO susceptibility with both single axis and coupled inputs

- Need to brief pilot to aggressively work to keep errors zero

- high gain  $\equiv$  aggressive closed loop behavior  $\rightleftarrows$  works on high frequency portion of pilot - vehicle transfer characteristics

- High freq  $\equiv$  quick or sharp initial response

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PQ Workshop 41, Page 4/1999

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## Flight Test Tasks (Cont.)

### Synthetic Tasks (Cont.)

- this is region where problematic (cliffy) phase lags, phase rates and rate saturation effects occur

- Tasks should be programmed to occasionally require inputs from pilot that may seem operationally unrealistic  
e.g. rapid, full throw inputs

- Primary objective of tasks is to expose PIO/dangerous overcontrol potential

- minimize risks of occurrence once aircraft is "certified"

- Hence, need to force test input sequences that stress the pilot-vehicle system to extremes even if unrealistic from an ops standpoint e.g. "klunk" inputs used by Saab

- Flight test needs to establish margins around the operational envelope

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## Flight Test Tasks (Cont.)

### Synthetic Tasks (Cont.)

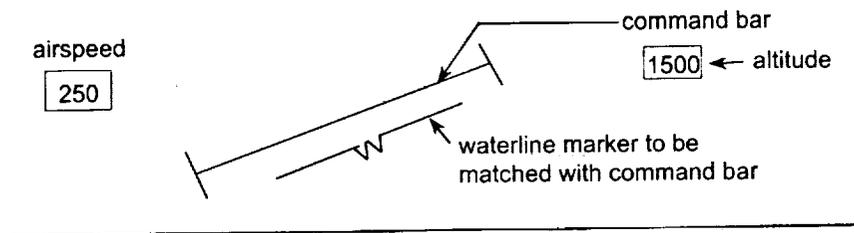
- Tracking bar programmable in both pitch and roll which the pilot chases with body axis fixed symbol such as a waterline pitch marker
  - This implementation has been successfully utilized on military aircraft by projecting this task on a HUD
  - demonstrated in Learjet projected on a head down LCD display
  - In either head up or head down implementation, can record tracking error in both pitch and roll and correlate with pilot input activity

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## Flight Test Tasks (Cont.)

### Synthetic Tasks (Cont.)



Learjet LCD Display of Tracking Tasks

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## Flight Test Tasks (Cont.)

### Synthetic Tasks (Cont.)

#### ■ Two types of tasks

##### 1. Discrete Tracking Task (DTT)

- combination of steps, ramps in both pitch and roll but "coordinated"
- can separately control amplitude of pitch and roll separately to match task to nature of aircraft being tested
- objective is to elicit both gross acquisition and fine tracking activity

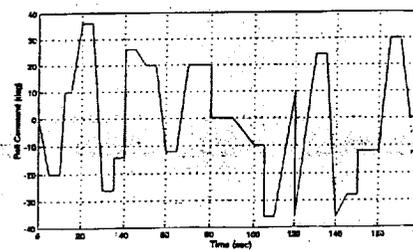
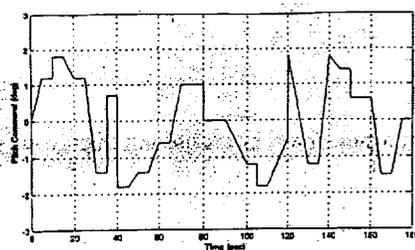
##### 2. Sum of Sines

- combination of sine waves of different frequencies
- 1st or 2nd order frequency roll off (filter)
- pitch and roll amplitudes separately controllable again to match task to aircraft being tested
- objective is to elicit aggressive fine tracking activity

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110 Waterloo Mall, Parsippany, NJ 07654

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## Flight Test Tasks (Cont.)

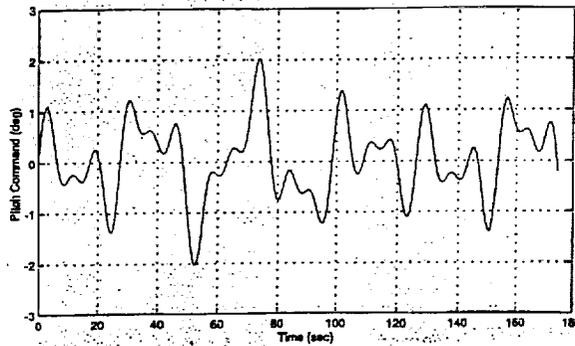


Discrete Tracking Task

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## Flight Test Tasks (Cont.)



Sum of Sines Tracking Task  
(similar in roll)

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PIO Workshop M.L. Perage 1999

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## Flight Test Tasks (Cont.)

### Other Considerations

- “Triggers” of PIO should be inherent in developed tasks whenever feasible
- Need to consider task environment issues
  - effects of turbulence
  - conditions of visual cues
- FTT’s must be tested against known problem configurations and consistently expose potential or latent “black holes”
- FTT’s must generally indicate “good” aircraft to indeed be good

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## Special Issues Pertaining to Civil Certification

- A major hurdle is to get past barrier from pilots or managers on test techniques that "transports are not flown this way" or that certain pilot inputs are unrealistic.
  - there needs to be recognition that flight test/certification test should establish adequate "margins"
  - ensure no "cliffs" on the edge of envelope
  - account for unusual inputs from "startle" factor

## Test Pilot Communication Tools

- Need proper tools to ensure orderly process for test pilots to solidify and effectively communication their evaluation or assessment to engineers, managers, and other pilots
- Comment Cards
  - checklist for comments
  - comments are meat of evaluation data
- Cooper-Harper Rating Scale
  - consideration of "average pilot"
  - cutoff for "exceptional attention, skill or strength" in civil certification?

## Test Pilot Communication Tools (Cont.)

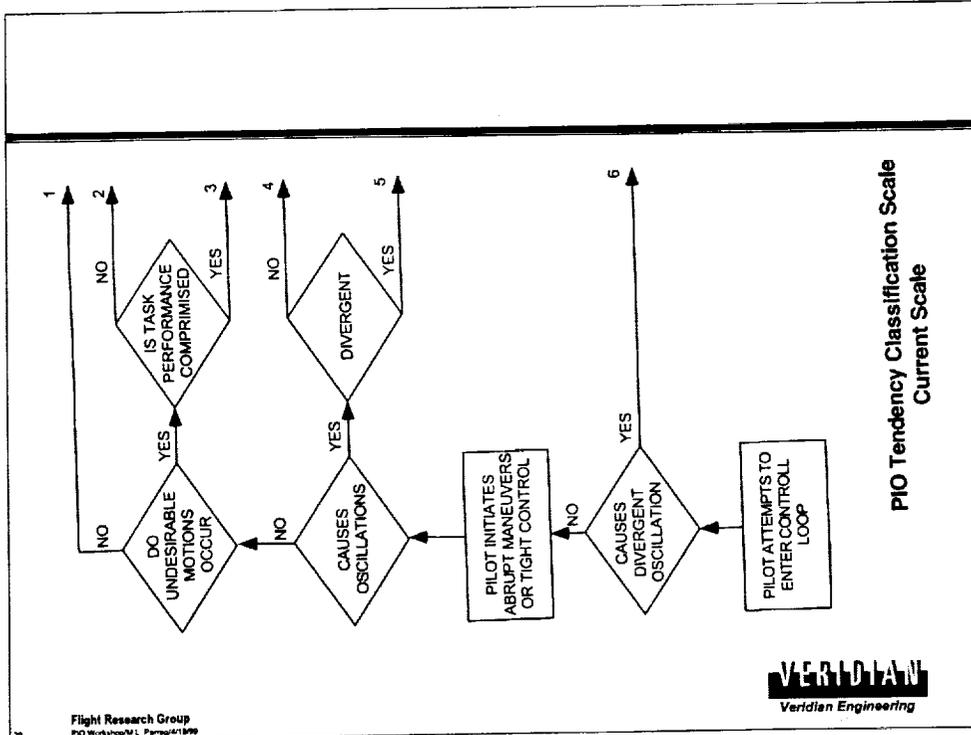
### ■ PIO Rating Scale

- current scale
- suggested modification

- too much arguing about PIO rating scale when most important pilot evaluation issue is task/FTT's that expose problems - rest is merely organizing how pilot reports what he has seen

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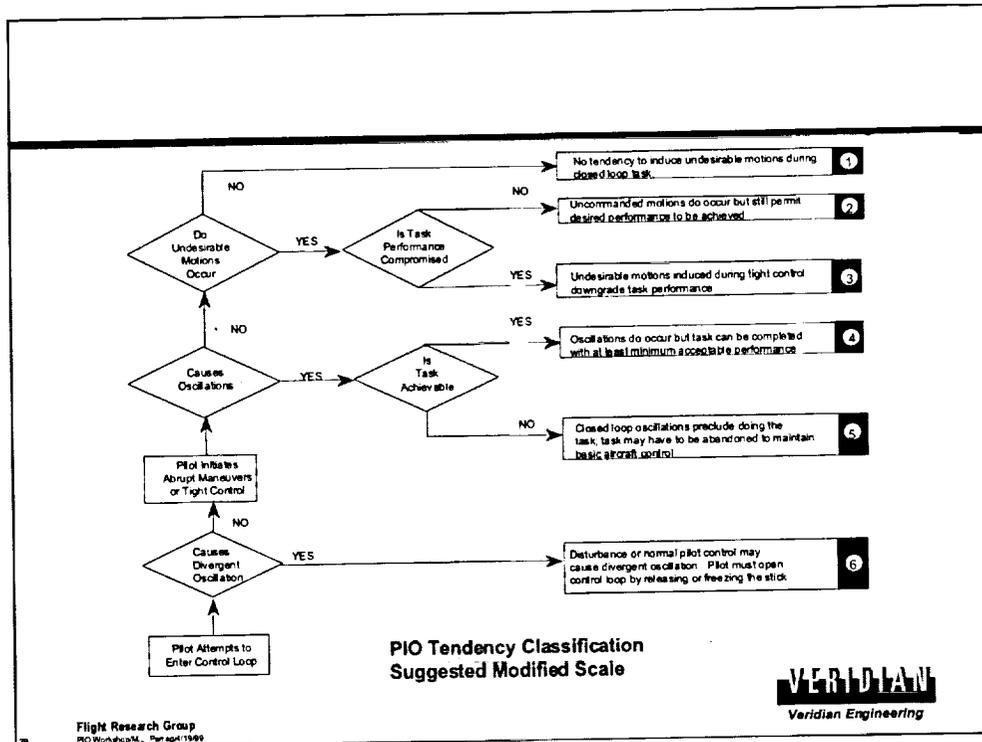
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PIO Tendency Classification Scale  
Current Scale



## Unique Instrumentation Requirements for PIO Related Flight Tests

### During Flight Test

- Data sampling rates 30 hz or higher for rigid body PVS dynamics  
i.e. fast variables
- Lower data rates for slow variables such as altitude airspeed
- should get derivative of aircraft rotational rates and perhaps even 2nd derivative - - - "jerk" motions
- instrument for  $n_{z_p}$ ,  $n_{y_p}$
- should instrument for actuator rates and control margins

## Unique Instrumentation Requirements for PIO

- In Operational Use
  - Flight Data Recorder
  - Sufficient data channels to record critical variable
  - Sampling rates for critical parameters need to be at least 15-20 hz

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## Management Issues Pertaining to PIO Problem

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## Management Issues

- Industry awareness of PIO is poor
- Lack of understanding of phenomenon and implications to
  - design process
  - flight test process
- Flight test teams need specialized training to improve ability to test FBW in general and for PIO in particular
  - exposure of test pilots and FTE's to a variety of PIO's in in-flight simulator aircraft is excellent conditioner for test teams
  - “A good scare is worth more than good advise”**
  - makes them “true believers” in PIO search process

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## Management Issues (Cont.)

- Managers need to support a structured approach to test process from early in design to service entry
  - use all the tools at their disposal, integrated recognizing each tool strengths and limitations
- Managers need to treat flight test as a process of discovery rather than as mundane validation of predictions
- What information from flight test needs to be communicated to the operational pilot
  - overcome the “marketing hurdle”

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## Flight Test Training

- Exposure of test pilots and flight test engineers to real PIO's in the variety of tasks presented earlier becomes an invaluable career experience to:
  - Appreciate the significance of the phenomenon
  - Appreciate the criticality of various tasks and of task environment towards the propensity to PIO
  - Ensure that these flight test crews will appropriately adjudicate any test planning process with regards to PIO in which they will participate in the course of their career

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## Flight Test Training (Cont.)

to reiterate

**“A good scare is worth more than good advice”**

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# **A Method for the Flight Test Evaluation of PIO Susceptibility**

**Thomas R. Twisdale & Michael K. Nelson  
412thTW/TSFT/USAF Test Pilot School**

**Handling qualities testing is the most important of all flying qualities testing**

**Handling qualities are the dynamics, or characteristics, of the pilot plus the airplane.**

**Handling qualities testing is based on three principles**

**model validation test method**

**build-up approach**

**completeness**

## **Model validation test method**

- 1. Predict the airplane response, based on a model.**
- 2. Test the prediction.**
- 3. Validate or correct the model, based on the test results.**

## **Build-up approach**

**Testing progresses from the lowest to the highest level of risk.**

## **Completeness**

**Evaluate the *FULL* spectrum of handling qualities.**

## **Three phases of handling qualities testing**

**Phase 1: Low bandwidth testing**

**Phase 2: High bandwidth testing**

**Phase 3: Operational testing**

## **Phase 1: Low bandwidth testing**

### **Purpose:**

**evaluate low bandwidth hq (smooth, low  
frequency, non-aggressive control)**

**familiarization**

**warm-up**

**"get acquainted"**

### **Test Maneuvers**

**open-loop (*NOT* handling qualities)**

**semi-closed-loop**

**low bandwidth maneuvering**

**low bandwidth tracking**

### **Test data**

**pilot comments**

**time histories**

## **Phase 2: High bandwidth testing**

### **Purpose**

**evaluate high bandwidth hq (abrupt, high frequency, aggressive, small and large amplitude control)**

**"stress testing"**

**"safety gate"**

### **Test maneuvers**

**HQDT (principally)**

**simulated carrier approaches**

**Test data: pilot comments and ratings (PIO and analog scale)**

### **Phase 3: Operational evaluation**

**Purpose: evaluate whether handling qualities are adequate to perform the design mission**

**Test maneuvers: depends on airplane and mission**

**Task performance standards: traceable to mission**

**Test data**

**pilot comments and ratings (Cooper-Harper, PIO, analog scale)  
measured task performance**

## **Phase 2: High bandwidth testing**

### **Purpose**

**evaluate high bandwidth hq (abrupt, high frequency, aggressive, small and large amplitude control)**

**"stress testing"**

**"safety gate"**

### **Test maneuvers**

**HQDT (principally)**

**simulated carrier approaches**

**Test data: pilot comments and ratings (PIO and analog scale)**

# HQDT

**special piloting technique:**

**track a precision aim point as aggressively  
and as assiduously as possible, always  
striving to correct even the smallest of  
tracking errors**

## **Objections to HQDT**

**pilots don't fly that way**

**OK for fighters, but not for large airplanes**

**causes degraded task performance**

**HQDT makes any airplane look bad**

**done for engineers, not pilots**

## Session V



 **ON-BOARD PIO  
DETECTION/PREVENTION** 



David B. Leggett  
AFRL/VAAD  
Wright-Patterson AFB; ~~Off 4443~~

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FAX: (937) 656-4000  
E-Mail: david.leggett@va.wpafb.af.mil

 **BACKGROUND** 

- **THE BEST WAY TO AVOID PIO PROBLEMS IS TO DESIGN THE FLIGHT CONTROL SYSTEM SO THAT THE AIRCRAFT DOES NOT HAVE ANY PIO TENDENCIES**
- But...
  - Aerodynamic prediction methods (CFD, wind tunnel) are not perfect
  - Design criteria and analysis methods are not perfect, particularly with regard to the effects of significant nonlinearities
  - Flight control changes to fix PIO problems detected late in the development cycle can be “expensive” to fix

2



## THEORETICAL BENEFITS



- Quick, cheap fix
- Valuable safety net in flight test, even if not intended for operational use
- Detection algorithms can provide valuable data during development and flight test

3



## KNOWN DRAWBACKS



- May only mitigate PIO tendency, not solve it
- Always impacts general handling qualities

4



## VARIOUS APPROACHES



- Suppression filters
- Rate limiting algorithms
- PIO detectors
- PIO preventers
  - Passive
  - Active
- Force cueing

5



## SUPPRESSION FILTERS

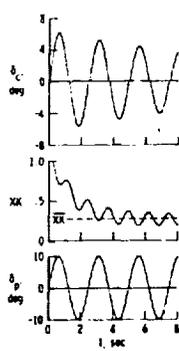


- Low-pass filter in the forward path to prevent pilot inputs from exciting PIO tendency
- Attenuates command and adds phase lag to the aircraft response, degrading general handling qualities, especially for high bandwidth tasks

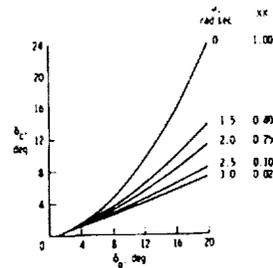
6



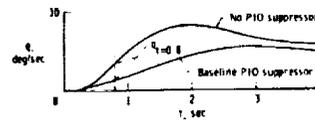
## SPACE SHUTTLE ADAPTIVE PIO SUPPRESSOR



Output from sine wave input,  
 $A = 10 \text{ deg}$ ,  $\omega = 2.5 \text{ rad/sec}$



Frequency-dependent attenuation



Pitch rate response to 15-deg  $\delta_p$  step input



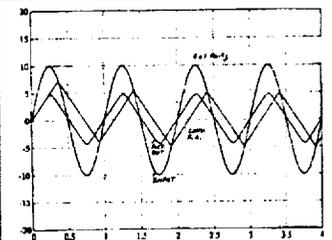
## RATE LIMITING ALGORITHMS



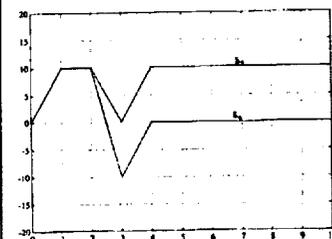
- Eliminates or reduces the phase lag due to rate limiting
- Introduces a bias between commanded output and actual output, attenuates command and reduces control power
- Removing bias causes “uncommanded motions”
- Only good for PIO tendencies caused by rate limiting



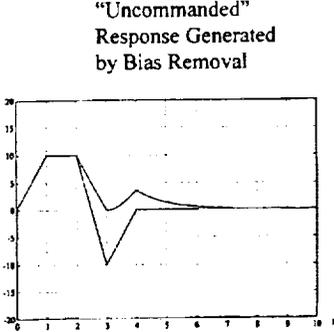
# RATE LIMITING ALGORITHM



Basic Concept



Bias generated by asymmetric input



"Uncommanded" Response Generated by Bias Removal



# RATE LIMITING EXPERIMENT ON LEARJET (Mar 93)



Pilot	Task	RLC	CHR	PIOR	Comments
A	BAT	Off	8	4	nonlinear, lumpy, seems like a delay but not time delay
		On	5	3	undesireable motions
	PA	Off	10	5	abrupt maneuvers get divergent behavior, large but slow amplitude divergence, no evidence during approach
		On	4	2-3	some lack of precision, 5 deg overshoots, sense that I'm in control, no tendency to get into divergence, precision not quite what I'd like, small wallowing, tendency to overcontrol, task compromised slightly
B	PA	Off	10	5	PIO prone, abrupt inputs do cause oscillations which may be divergent
		On	4, 5	2,2	no difficulties with PIO, small tendency to be imprecise, little more tendency to wallow when you try to be precise, trying to be more precise brought out tendency to overcontrol
C	PA	Off	10	6	no way to stay in the loop on that, holy s---t!, PIO max on the scale, stick all the way over and aircraft still going the other way
		On	-	-	still goes slow, could definitely feel rate limiting but it was not PIO prone like the last one, big difference



## PASSIVE PIO PREVENTION



- Warning activated by detection of PIO, rate limiting, or other related phenomena
- Warning can be:
  - Light
  - Audio warning
  - Warning on HUD
  - Force feedback through stick
- Pilot must recognize and adapt

10



## ACTIVE PIO SUPPRESSION

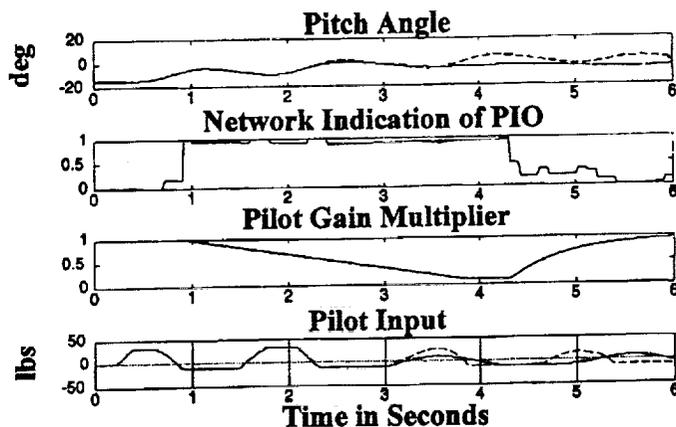


- Changes to control system activated by detection of PIO, rate limiting, or other related phenomena
  - Reduce forward path gain
  - Pass pilot input through low-pass filter
  - Force feedback through control stick
- May have more adverse effects than the PIO

11



## PIO DETECTION AND ACTIVE SUPPRESSION



13

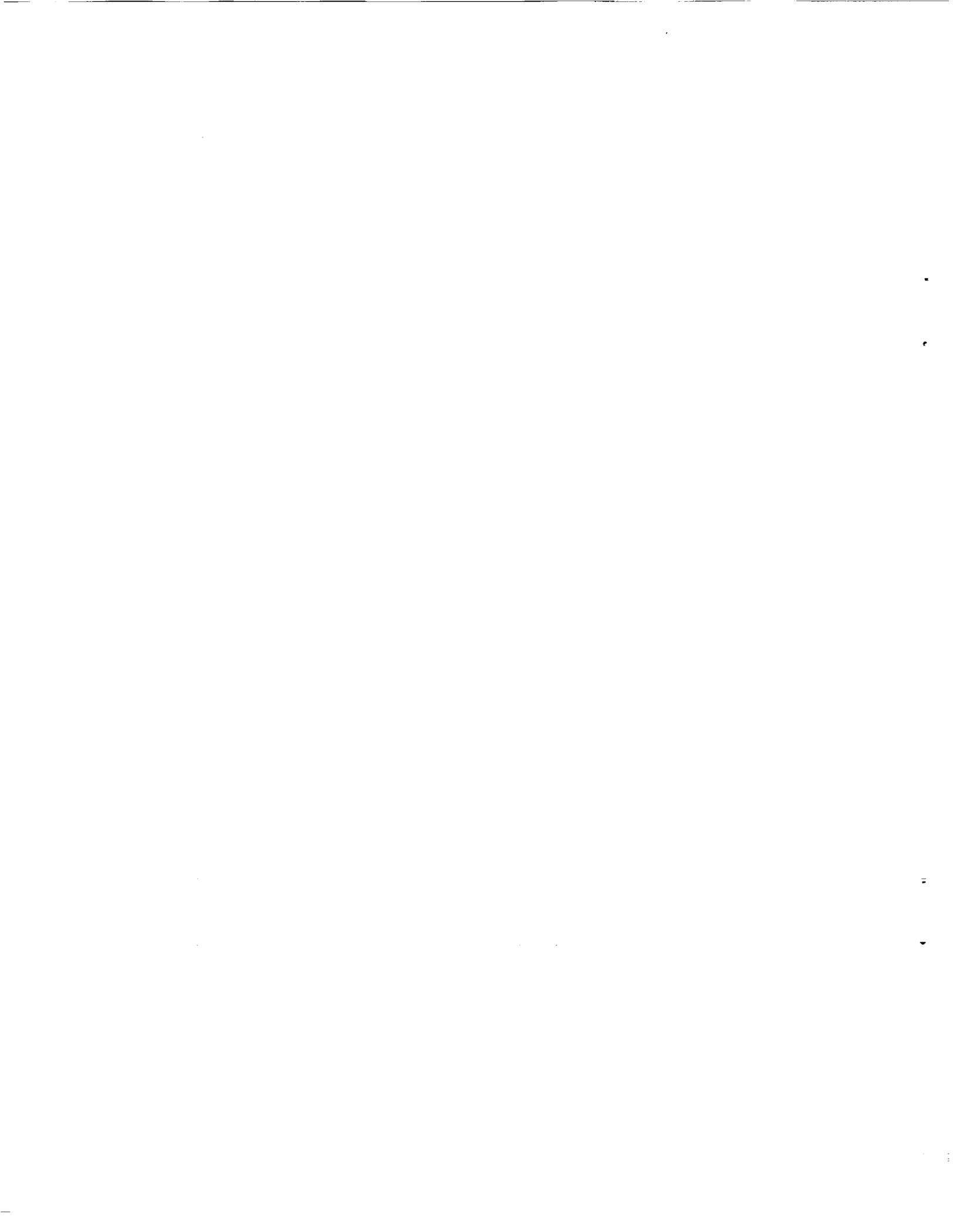


## CONCLUSIONS



- These techniques can work
- Although not the first choice, they may present a program with an alternative to "complete redesign" or "tell pilot not to do that"
- Detection algorithms provide handy data analysis capability
- There are serious drawbacks, design of these algorithms should not be taken lightly

14



*Accurate Automation Corporation*

## **Real Time PIO Detection and Compensation**

**Chadwick Cox, Carl Lewis,  
Robert Pap, Brian Hall  
Accurate Automation Corporation  
7001 Shallowford Road  
Chattanooga, TN 37421  
ccox@accurate-automation.com  
423-894-4646**



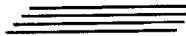
*Accurate Automation Corporation*



*Accurate Automation Corporation*

## **Thanks**

- **Charles Suchomel - AFRL, COTR**
- **Brian Stadler - AFRL**
- **David Legget - AFRL**
- **Thomas Cord - AFRL**
- **Ba Nguyen - AFRL**



*Accurate Automation Corporation*

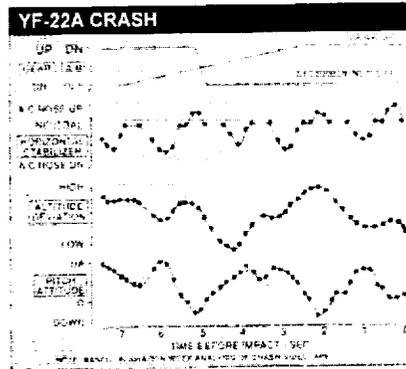


## Neural Network Compensation Strategy for Preventing Pilot-Induced Oscillations

Air Force Phase II SBIR F33615-96-C-3608  
COTR: Chuck Suchomel AFRL/VACD

**Objective:** Develop a Smart Neural Network-Based Controller to Prevent Pilot-Induced Oscillations.

1. Recognize Pilot-Induced Oscillations In Data From Events Where PIO Have Played a Major Part
2. Designed a Neural Network To Recognize the PIO and Help The Pilot to Fly Out of the Problem
3. Designed an Advanced Hardware Controller to Validate the Concept
4. Patent Pending



## Results to Date

**Patent will be issued soon**

**Detector/Compensator tested in closed loop with simulated configurations on AFRL 6-DOF piloted simulator**

**Detector tested with F-16 PIO data, HARV PIO data, and simulated NT-33 data (MS-1)**

**Detector/Compensator tested in open and closed loop with simulated F-16**



## Results to Date

### Designed hardware

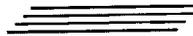
**VME**

**DSP**

**NNP<sup>®</sup> interface**

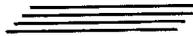
**VME to 1553 interface**

**A/D, D/A, digital interfaces**



## Presentation Topics

- **PIO Detection and Compensation**
- **Simulation Testing**
- **PIO Hardware**



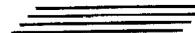
## Concept

- **While a PIO occurs, a detector flags the PIO.**
- **If no PIO is occurring, the detector outputs a zero.**
- **When the detector flags a PIO, a compensator is engaged.**



## PIO Detector Goals

- **Real time operation**
- **Accurate**
- **Robust**
  - configurations
  - pilots
  - noise
- **Simple**



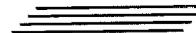
## PIO Compensator Goals

- **Activated when PIO occur**
- **Never active when PIO not occurring**
- **Stops PIO**
- **Acceptable to Pilots**



## PIO Detection

- **PIO detection is simple and clean**
  - simple algorithm
  - runs in real time
  - only straightforward preprocessing is required
  - works in longitudinal and lateral axes
  - works for many configurations
  - accurate



## PIO Compensation

- **How to compensate for PIO is still unresolved.**
  - We have tested simple authority reduction and a PIO filter
  - Pilot's do not like to have their authority reduced
  - Sometimes different situations call for different types of compensation
  - More testing is necessary.



## Algorithm Development

- We used MS-1 simulation data, HARV data, and F-16 simulation data to develop the detector.
- An iterative process was used to train the detector.
- The compensator was developed with simulated HAVE PIO configurations.

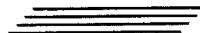
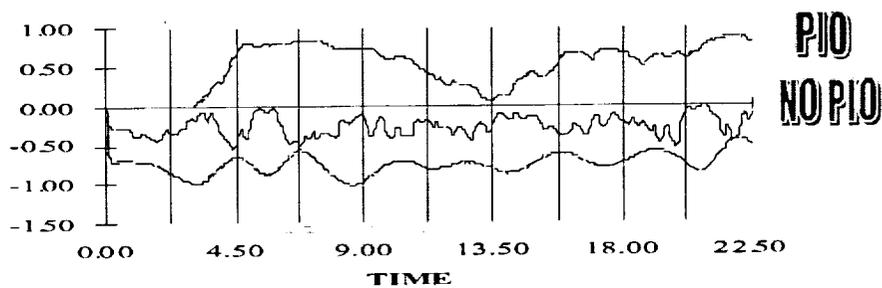


## Simulation Testing

- Tested detector with MS-1 PIO data
- Tested detector/compensator with simulated HAVE PIO configurations and simple pilot model
- Tested detector, advisory, and compensator in LAMARS simulator



## Detection of MS-1 Simulated PIO



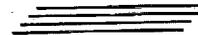
## Piloted Simulation Testing

- **Performed in AFRL LAMARS high-fidelity motion base simulator**
- **Tested a PIO detector and two compensators**
- **Gathered data to improve detection and compensation methods**



## Piloted Simulation Testing Rational

- **Only human in the loop testing can tell you how a compensator or advisory will effect the performance of a pilot.**
- **Pilot models are not adequate.**
  - They are good only for initial testing.
  - Not all problems can be uncovered with pilot models.



## Major Questions

- **Does the detector perform adequately?**
  - Must not trigger when it shouldn't
- **Does the compensator perform adequately?**
  - Must not cause a bigger problem when it is on.
  - Preferably must allow the pilot to perform his task.



## Detection Issues

- **Does the detector perform adequately?**
  - Does it stay off when there is no PIO?
  - Does it come on when there is a PIO?
  - Does it work across a wide range of configurations?
  - Does it work across a wide range of pilots?
  - Is it robust to noise?



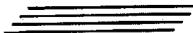
## Compensation Issues

- **Does the compensator perform adequately?**
  - Does it stop PIO?
  - Can the task still be performed?
  - Do pilots mind having their authority reduced?
  - Does filter induced delay cause other problems?



## Compensation Issues

- **Do different PIO call for different compensation?**
  - Use gain compensation with explosive PIO?
  - Use filter compensation with mild to medium PIO?
  - Use other methods?



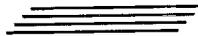
## Compensator Types

- **Gain Compensator**
  - Ramp in
  - Ramp out
  - Minimum authority
  
- **Filter Compensator**
  - Ramp in
  - Ramp out
  - Minimum authority



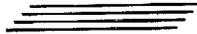
## Simulation Testing Methodology

- **Succinct matrix**
  - HAVE PIO and landing task
  - HAVE LIMTS like configurations with tracking task
- **Short look instead of long look**
- **Random presentation**
- **Repeats allowed**
  - this allowed us to use short look without confidence levels



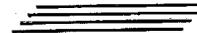
## **Simulation Testing Matrix Advisory/Compensation Options**

- **Four Cases**
  - **PIO detection but no advisory, no compensation**
  - **Detection and advisory, no compensation**
  - **Detection and no advisory, compensation**
  - **Detection and advisory, compensation**



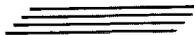
## **Simulation Testing Methodology - Pilots**

- **one Navy test pilot, one civilian acrobatic pilot, and five Air Force test pilots**
- **prebriefed pilots**
- **did not lead the pilots**
- **tried not to let pilots compare configurations**
- **performance feedback provided at end of run**



## **Simulation Testing Methodology - Pilots**

- **made pilots go through the scales when giving ratings**
- **rating/Questionnaire cards with pilot in cockpit**
- **debriefed the pilots**
- **frequent breaks**



## **Simulation Testing - Pilot Subjective Data**

- **Pilot briefings**
  - configurations, tasks, motion, ratings, adequate and desired
- **Pilot comment card**
  - PIO scale (Mike Parrag - Veridian) and Cooper-Harper scale
  - Questions
- **Pilot's asked to give frank assessment of algorithms**



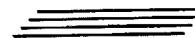
## Simulation Testing - Configurations

- **HAVE PIO - Category I**
  - Baseline Longitudinal 2-1,3-1,5-1
  - Primary Longitudinal 2-5, 5-9, 5-10
  - Secondary Longitudinal 2-8, 3-12, 3-13
  
- **HAVE LIMITS - Category II**
  - 2P, 2DU, 2D, 2DV
  - Rate limit adapted to pilot to force PIO



## Simulation Testing - Pilots' Tasks

- **Offset landing**
  - pilot must land aircraft within target zone starting from an offset approach
  - HAVE PIO configurations
  
- **Discrete tracking**
  - pilot tracks steps and ramps
  - HAVE LIMITS



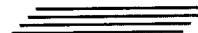
## Simulation Testing - Time Series Data

- All detector and compensator inputs, internal variables, and outputs
- aircraft state variables
- pilot outputs
- task and performance data
- pilot PIO indicators (trigger pulls at about where a PIO occurs)



## Simulation Testing Results

- Detector works very well in pitch and roll
- Gain compensator stops PIO but pilots don't like it
- Filter compensator had problems
- Much analysis still to be done



Report number 20 is missing slides 31 to 34; they were unavailable at the time of publication.

*Accurate Automation Corporation*

**Simulation Testing Result -  
Divergent PIO**

  
*Accurate Automation Corporation*

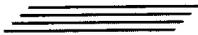
*Accurate Automation Corporation*

**Simulation Testing Result -  
NO PIO**

  
*Accurate Automation Corporation*

*Accurate Automation Corporation*

# **Simulation Testing Result - NO PIO**

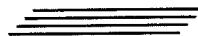


*Accurate Automation Corporation*



*Accurate Automation Corporation*

# **Simulation Testing Result - NO PIO**



*Accurate Automation Corporation*



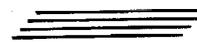
## **Simulation Testing Results - Pilot Comments**

- **Advisory well correlated to pilot assessment of PIO**
- **Some pilots found advisory helpful**
- **Some pilots said advisory didn't give them additional information**
- **Some pilots commented on timeliness of detection**



## **Simulation Testing Results - Pilot Comments**

- **Pilots said gain compensation stopped PIO, but interfered with task**
- **Delay induced by filter compensator caused problems**
- **Pilots felt that motion helped them with tasks, especially landing**



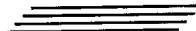
## Simulation Testing Results - Observations

- Pilots improved their performance over time
- One "golden arm" pilot could fly almost anything
- Pilots sometime adapted to gain reduction



## PIO Compensation Hardware

- board hosts PIO detection and compensation algorithms
- DSP
- includes interface to multiple AAC NNPs.
- VME bus with 1553 interface
- A/D, D/A, and digital interfaces



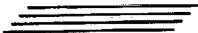
## Conclusions

- Developed a *real-time* PIO detector
- Developed a *real-time* PIO compensator
- Tested detector and compensator in a high fidelity piloted simulators
- Continuing simulation testing
- Developing hardware



## Next Steps

- Analyze data
- More simulation testing
  - larger matrix, operational pilots, new advisories, force feedback
- Flight Testing
- Develop PIO Classifier
- Develop a good compensation method



## PIO Detection with a Real-time Oscillation Verifier (ROVER)

David G. Mitchell  
Technical Director  
Hoh Aeronautics, Inc.

Pilot Induced Oscillation Research Workshop  
NASA Dryden Flight Research Center  
8 April 1999



## Prevention of PIOs in Flight

- Fundamental goal is to prevent PIOs by design
  - On-board detector could be a valuable flight test tool
  - Application for failures, unusual loadings and flight conditions
- Monitor airplane responses and pilot inputs to look for:
  - Oscillations of proper frequency range
  - Airplane out of phase with pilot
  - Amplitudes of input and output large
- Concept developed under current contract
  - Has not actually been applied real-time
  - Applying for patent
  - Looking for follow-on funding for further development



## Real-Time Detection of PIOs

- Time histories of dozens of PIOs have been examined in detail
- Underlying conclusions:
  - There is no clearly identifiable “pre-PIO” condition
  - Many of the precursors to PIO occur in normal operation
  - It will not be possible to detect and stop a PIO **before** it starts
  - The best we will be able to do is detect one in the first half-cycle (or so)

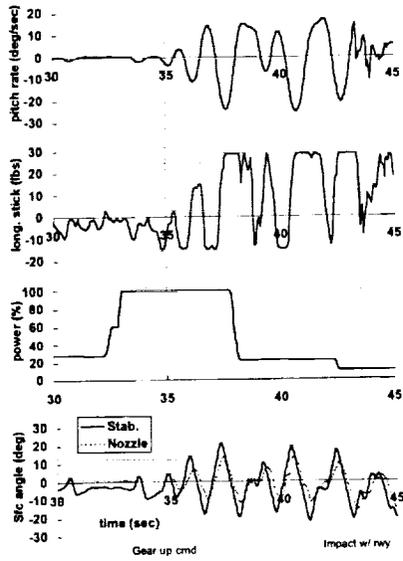
HAL 

## Real-time Oscillation VERifier (ROVER)

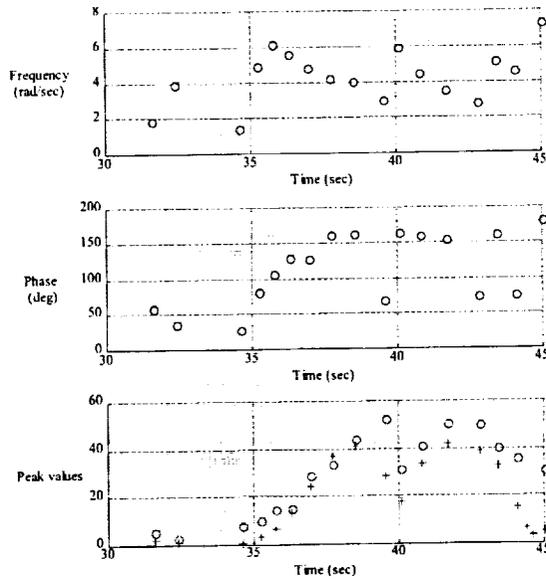
- Assumptions:
  - Pilot operates more or less sinusoidally
  - Pilot adopts synchronous behavior in PIO
  - Airplane is 180° out of phase with pilot in a PIO
- Apply a moderate amount of filtering
  - Bandpass to emphasize range of expected PIO frequencies
  - Both input and output filtered to minimize impact
- Test for:
  - Oscillation frequency within range for PIO
  - 90° phase lag between control input and pitch rate
  - Proper amplitude of input and output

HAL 

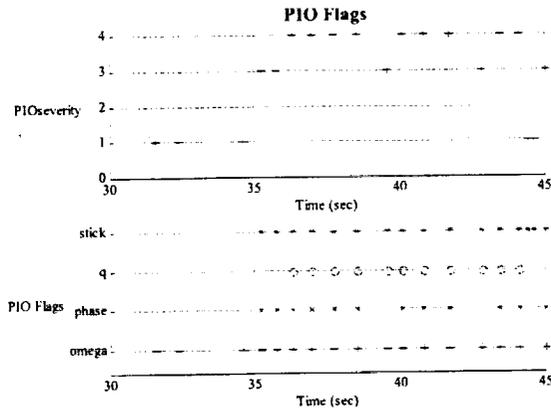
# YF-22A Mishap



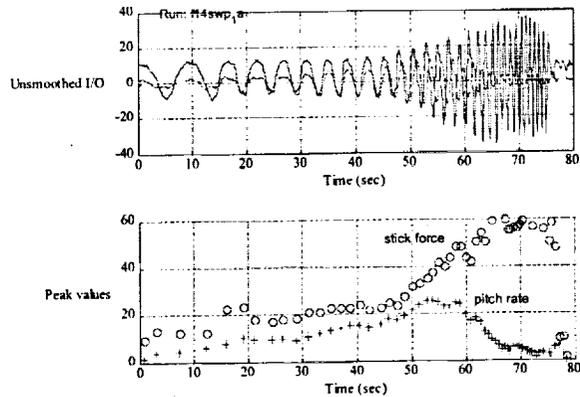
# Output for YF-22A Mishap



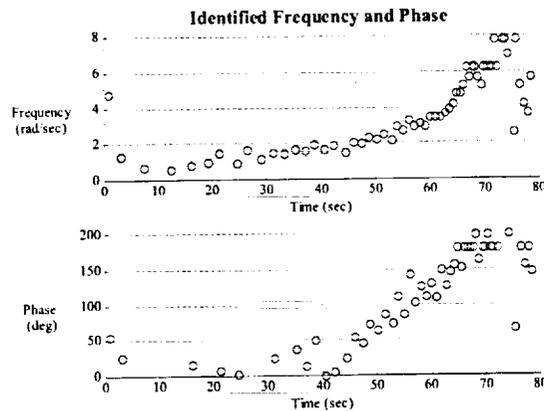
# Output for YF-22A Mishap



# Application as a Flight Test Tool: Time-domain verifier for frequency sweeps



## Application as a Flight Test Tool: Time-domain verifier for frequency sweeps



HAL 

## Continuing Development

- Extend to roll
- Extend to normal acceleration
- Select best filters for bandpass, removing noisy data
- Requires tailoring
  - Different flight conditions (higher thresholds up-and-away)
  - Different cockpit effectors (force vs. displacement)
  - Adapt to failures (reduce thresholds if sensors lost)
- Active intervention vs. alerting
  - Should depend upon complexity of flight control system, degree of instability, mission roles
  - Form of active intervention will depend upon flight condition

HAL 



# Pilot Opinion Ratings and PIO

Thomas R. Twisdale & Michael K. Nelson  
412thTW/TSFT/USAF Test Pilot School

See Paper no. 4 in Appendix 3



# **THE NEED FOR PIO DEMONSTRATION MANEUVERS**

Vineet Sahasrabudhe  
David H. Klyde  
Systems Technology, Inc.

David G. Mitchell  
Hoh Aeronautics, Inc.

Pilot-Induced Oscillation Research:  
The Status at the End of the Century  
NASA Dryden Flight Research Center  
6-8 April 1999

## **OVERVIEW**

- Identify relevance of demonstration maneuvers for PIO
- Review USAF Handling Qualities Demonstration Maneuvers program
- Exposing PIO
  - Probe-and-drogue refueling example
  - HUD tracking example
- The need for PIO specific maneuvers
- Additional candidate PIO demonstration maneuvers

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## **RELEVANCE TO PIO**

- Objective of the USAF program was to develop a catalog of repeatable maneuvers to evaluate closed-loop handling qualities
- Some of the maneuvers included in the final catalog also exposed PIO and/or PIO tendencies
- The continued occurrence of PIO in operational aircraft (military and commercial) indicates a strong need to develop a similar catalog for PIO

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## **DEMONSTRATION MANEUVERS PROGRAM BACKGROUND**

- Phase II SBIR for the USAF Flight Dynamics Directorate
  - Air Force Technical Contact: Thomas J. Cord
- Phase I results published as STI TR-1298-1 and as Appendix C of WL-TR-94-3162
- Proposed Maneuver Catalog published as STI ITR-1310-1
  - Distributed to USAF FIGC mailing list for review
- STEMS Flight Test Evaluation with the NASA F/A-18 HARV published as STI ITR-1310-2 and as WL-TR-97-3002
- Phase II Results published as WL-TR-97-3099 & WL-TR-97-3100
  - Volume I: Maneuver Development Process (-3099)
  - Volume II: Maneuver Catalog (-3100)

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## **MISSION-ORIENTED REQUIREMENTS**

- Requirements are based on Mission Task Elements (MTEs) that relate to actual operations
- References to aircraft size are removed
- Allow for multiple response-types
- Provide predicted handling qualities
- Demonstration maneuvers are designed to complement the mission-oriented approach

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## **HANDLING QUALITIES DEMONSTRATION MANEUVERS**

- Evaluate *all* aircraft types (military and civil) and mission tasks
- Provide consistent maneuver definitions including desired/adequate performance requirements
- Evaluate total system: flight controls, pilot-vehicle interface, advanced displays and vision aids, etc.
- Provide ultimate check of handling qualities through piloted evaluation

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## MANEUVER CATEGORIES

- Non-Precision, Non-Aggressive
  - Takeoff, Landing, Waveoff/Go-Around
  - Heading and Altitude Changes
- Non-Precision, Aggressive
  - Air-to-Air Gross Acquisition
- Precision, Non-Aggressive
  - Precision Offset Landing
  - Attitude Capture and Hold
- Precision, Aggressive
  - Air-to-Air Fine Tracking

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## MANEUVER EVALUATIONS

- Flight Test Evaluations
  - NASA Dryden F/A-18 HARV: STEMS
  - USAF TPS HAVE GAS II: Probe-and-Drogue Refueling
  - USAF TPS HAVE LIMITS: HUD Tracking
  - General aviation aircraft: numerous maneuvers
- Flight Test Reviews
  - Large aircraft flying qualities (TIFS): Precision Offset Landing
  - USAF TPS HAVE CAP: Precision Offset Landing
  - USAF TPS HAVE TRACK: Simulated Aerial Refueling
- Pilot-in-the-Loop Simulation
  - NASA Dryden SR-71 Simulator: Supersonic Maneuver Set
  - McDonnell Douglas: PIO maneuver development

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## **MANEUVER CATALOG**

- Final catalog contains 36 maneuvers
  - Flight test evaluations: 18 Maneuvers
  - Simulator evaluations: 16 Maneuvers
  - 5 maneuvers need refinement
- Catalog spans the range of piloted control
- Flight conditions range from post-stall to supersonic, and from takeoff to landing
- Catalog is a living document
  - Revisions and additions are expected as new research is conducted

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## **EXPOSING PIO**

- Demonstration Maneuvers that have produced flight test PIOs
  - Aerial refueling, particularly probe-and-drogue
  - HUD tracking
  - Precision offset landing
- Demonstration Maneuvers that have exposed PIO tendencies
  - Air-to air and air-to-ground fine tracking
  - Attitude captures
  - Gross acquisitions (often expose Category II tendencies)

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## RECENT EVOLUTION OF PROBE-AND-DROGUE REFUELING

- USN F-14 Dual Hydraulic Failure Study (1991)
  - Revealed potential explosive nature of probe-and-drogue refueling task for severely rate limited configurations
  - Formation flying (prior to hook-up) did not expose poor handling qualities
  - Tracking drill devised to "shake out" configurations prior to hook-up
- USAF TPS HAVE GAS (1993)
  - Evaluation of different response-types using probe-and-drogue hook-up task
  - Handling qualities performance requirements (based on number of attempts to achieve three successful hook-ups) were not sufficiently discriminating
- Notice of Change to MIL-STD-1797A (1995)
  - HAVE GAS task with additional requirement to avoid contact with basket webbing for desired performance
- USAF TPS HAVE GAS II (1997)

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## HAVE GAS II PROGRAM SUMMARY

- USAF TPS Class 96B Test Management Project conducted in spring 1997
- Objective: Identify the task that best reveals aircraft closed-loop probe-and-drogue refueling handling qualities
- Seven flight test sorties: NASA F/A-18 (4 Sorties) and USAF variable stability NT-33A, operated by Calspan, (3 sorties)
- Candidate evaluation tasks: Hook-Up, Tracking, and Aiming Tasks
- Both qualitative and quantitative results clearly indicated that the tracking task best exposed closed-loop handling qualities
- To capture potential problems close-in to the basket, the hook-up task should be performed in concert with the tracking task

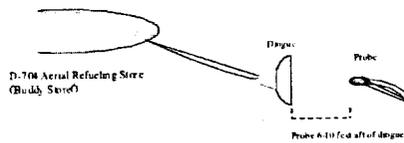
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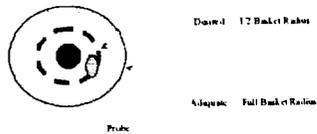


# DROGUE TRACKING CONFIGURATION

Side View



View From Cockpit



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# DROGUE TRACKING TASK FOR PIO

HAVE GAS II  
Video Example

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## **PROBE-AND-DROGUE TASK FOR PIO: CONCLUSIONS**

- Probe-and-drogue refueling has exposed all three PIO Categories in flight test
- HAVE GAS II program defined repeatable evaluation tasks based on drogue tracking and hook-ups
- Turbulence can have a significant impact on task performance and should therefore be accounted for in the evaluation process
- A method should be employed to verify drogue tracking distance (chase plane, differential GPS, etc.)

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## **HUD TRACKING TASKS FOR PIO**

- Recent Experience
  - USAF TPS HAVE LIMITS
  - McDonnell Douglas ground simulation comparison study
  - STI development of pilot evaluation tool (PASS) using sum-of-sines tracking tasks
  - HAI PIO simulations on LAMARS using discrete ("step-and-ramp," "Calspan" or "SAAB") tracking tasks
- Sum-of-Sines effective for identifying pilot dynamics and PIO tendencies, especially Category I
- Discrete Tracking effective for identifying PIO tendencies, especially Category II

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# HUD TRACKING TASKS FOR PIO

HAVE LIMITS

Video Example

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## HUD TRACKING TASKS FOR PIO: CONCLUSIONS

- There may be initial pilot reluctance to sum-of-sines task
- Discrete tracking is most effective as a two-axis task
  - Reduces pilot "learning"
  - Exposes both pitch and roll problems
- Verbal readouts not effective
  - Introduces undesired variability with commands
  - Must be single-axis only
  - Potential for pilot confusion over command values
  - No way to monitor tracking performance
  - Must be steps only, since "ramps" cannot be introduced verbally

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## **DEMONSTRATION MANEUVERS FOR PIO**

- Need for dedicated PIO Demonstration Maneuvers
  - PIO is not an operational event
  - PIO testing should be distinct from handling qualities
  - Some testing will be inconsistent with operational testing (e.g., HUD tracking or close formation with a transport)
- Additional candidate PIO Demonstration Maneuvers
  - SAAB Klunk method
  - HQDT
  - Rapid attitude captures
  - Others?

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# REPORT DOCUMENTATION PAGE

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